

Evolution of Superconductivity with Increasing Disorder in Two Dimensions



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The object

✓ Thin Disordered Superconducting films



quasi-2D:
electronic spectrum is 3D

$$l, \lambda_F < d < \xi, l_T$$

d - the thickness of the film

l - the mean free path

λ_F - Fermi wave length

ξ - the superconducting coherence length

l_T - the thermal coherence length



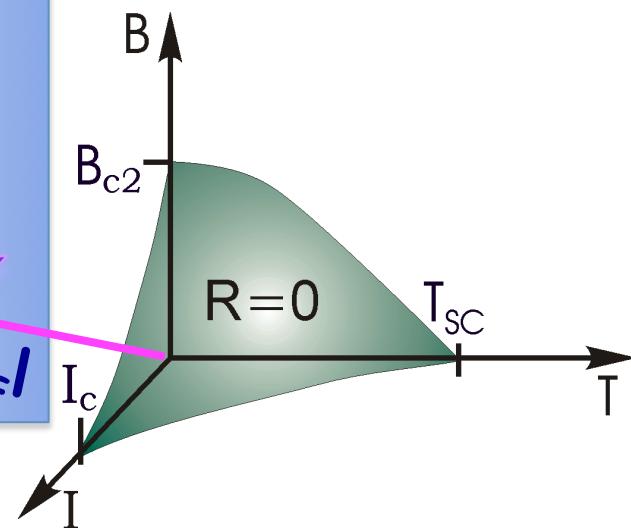
$$k_B T \tau / \hbar \ll 1$$

$$R_{sq} = \frac{\hbar}{e^2} \frac{3\pi^2}{k_F^2 l d}$$

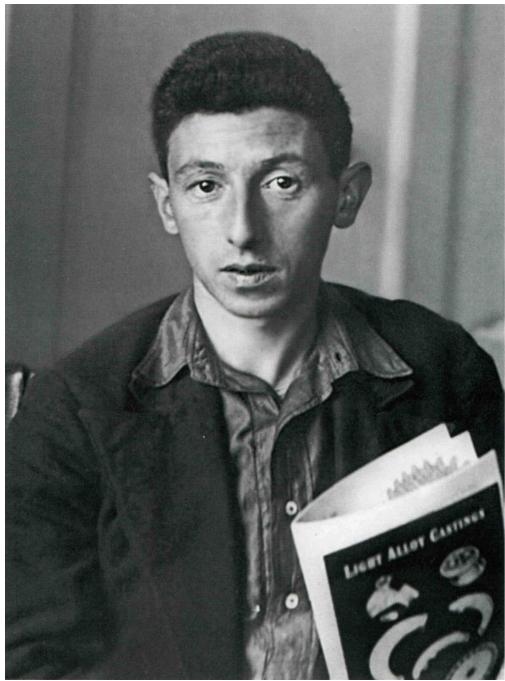
$$R_{sq} = \rho / d$$

($n, d, k_F l$)

disorder
 $R_{sq}, n, d, k_F l$



Evolution of Superconductivity with Increasing Disorder in Two Dimensions



The first studies of superconductivity in the presence of disorder were performed by A.I. Shalnikov
(Institute for Physical Problems, Russia).

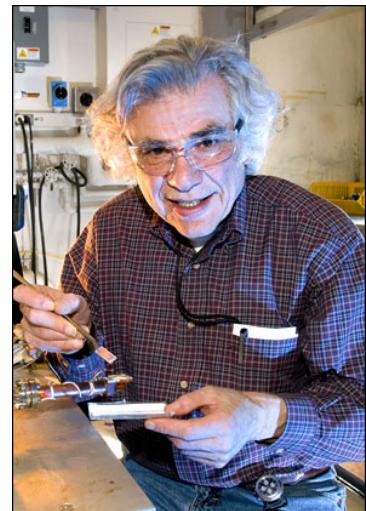
A. Shalnikov, Nature 142, 74 (1938)
A.I. Shalnikov, ZhETF 10, 630 (1940)

Amorphous metals:
lead (Pb), tin (Sn) and thallium (Tl) films
with thickness between 1 and 200 nanometers (!)

This was the first observation of suppression of T_c with decreasing thickness in thin superconducting films

Evolution of Superconductivity with Increasing Disorder in Two Dimensions

It is clear that T_c correlates much better with R_{\square} than with thickness or ρ . !!!



PHYSICAL REVIEW B

VOLUME 1, NUMBER 3

1 FEBRUARY 1970

Destruction of Superconductivity in Disordered Near-Monolayer Films*

MYRON STRONGIN, R. S. THOMPSON, O. F. KAMMERER AND J. E. CROW

Brookhaven National Laboratory, Upton, New York 11903

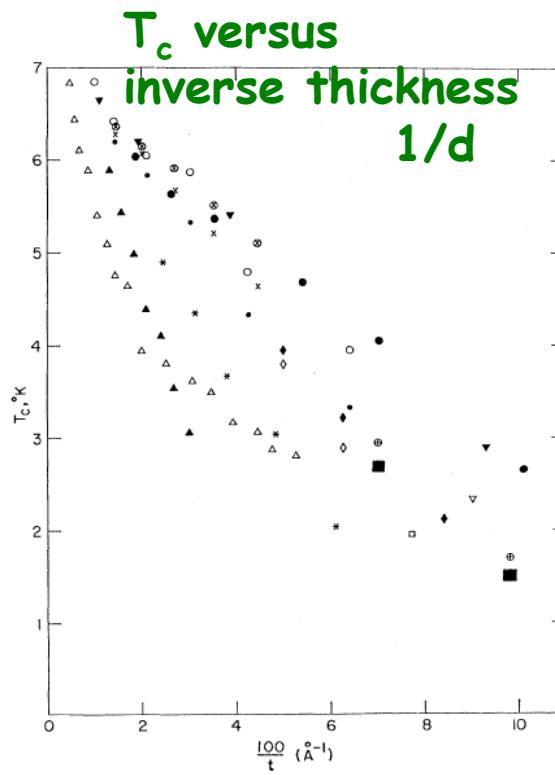
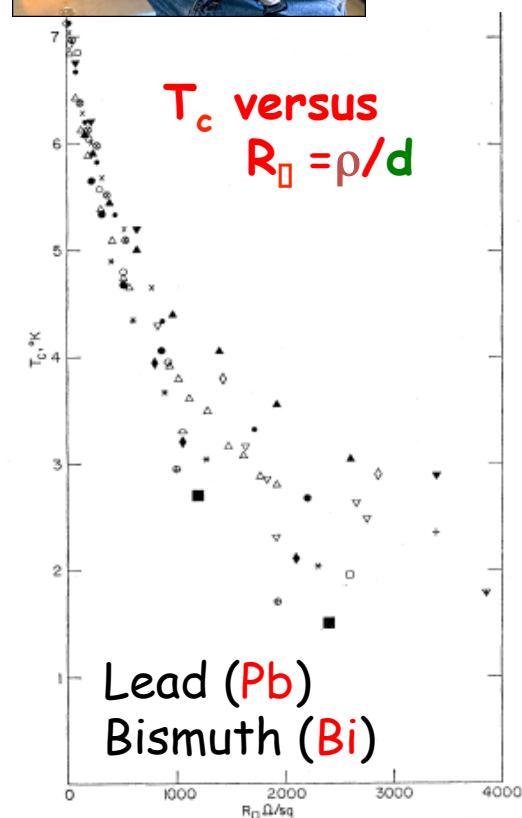


FIG. 6. T_c versus inverse thickness (see Fig. 5 for symbol notation).

Fig. 5. T_c versus R_{\square} where R_{\square} is the resistance/sq area:
 ⊖, ■—Pb on Ge; +—Pb on Al_2O_3 ; ♦, ◇—Pb on Ge (deposited at room temperature); *—Bi on SiO_2 ; ▽, ⊕, ○, *, ●, △, ▲, ▼—Pb on SiO_2 .

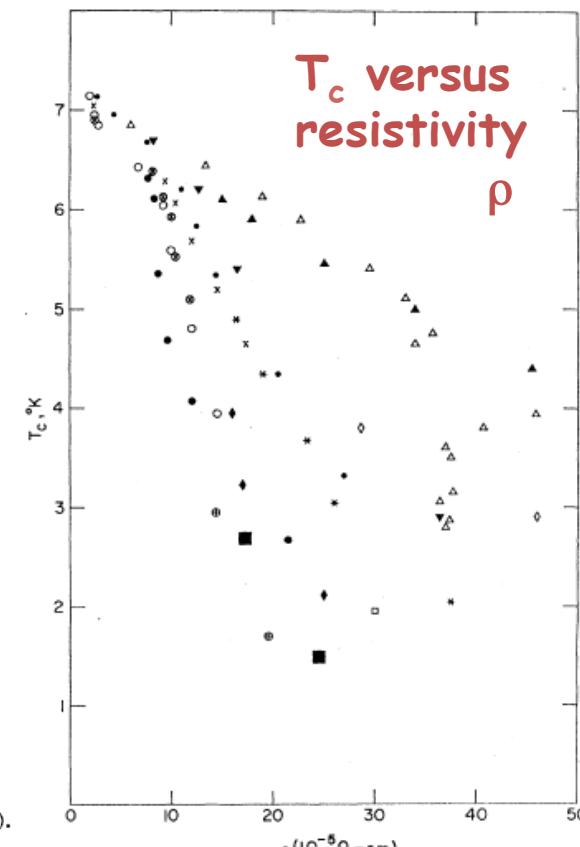
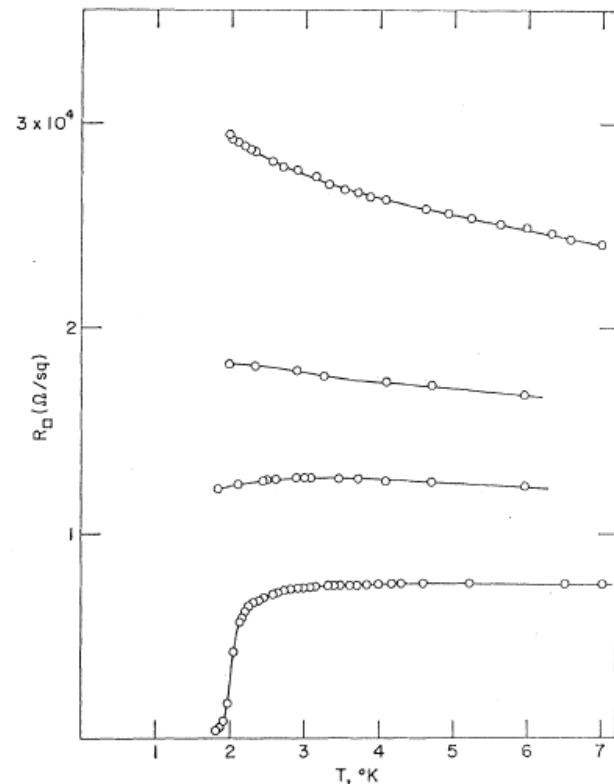


FIG. 7. T_c versus resistivity ρ (see Fig. 5 for symbol notation).

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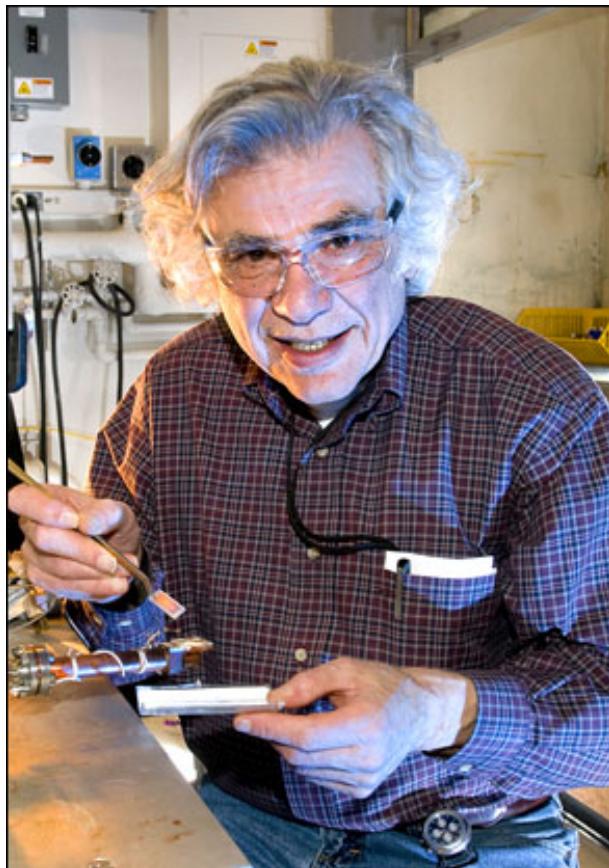


In the regime where the films first become electrically continuous, the resistance in the normal state is extremely high (greater than about 10 000 Ω/sq), and T_c is drastically reduced and is usually below the lowest temperature achievable with our cryostat. Also, in this regime where the films first become continuous, the normal-state resistance usually increases with decreasing T according to $R_0 e^{+\langle E \rangle / kT}$. This, of course, is in contrast to the usual metallic behavior where R decreases with decreasing T .

activated behavior of resistance

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I. The larger the sheet resistance
the smaller the superconducting critical temperature

II. The critical temperature correlates with the
sheet resistance much better than with the
thickness or resistivity

$$T_c = \text{function } (R_s)$$

III. Non-superconducting ultrathin films
demonstrate activated behavior of the resistance

Superconductor – Insulator transition

Anderson's theorem

predicts that nonmagnetic impurities have **no effect** on superconductivity

A.A. Abrikosov and L.P. Gorkov, Sov. Phys. JETP 8, 1090 (1958) (Phys. Rev. B 49, 12337 (1994))
P.W. Anderson, J. Phys. Chem. Solid 11, 26 (1959)

This theorem does not consider

enhancement
of electron-electron interaction
with increasing disorder

the effect
of Anderson localization

weak disorder \longleftrightarrow **strong disorder**

Fermionic mechanism

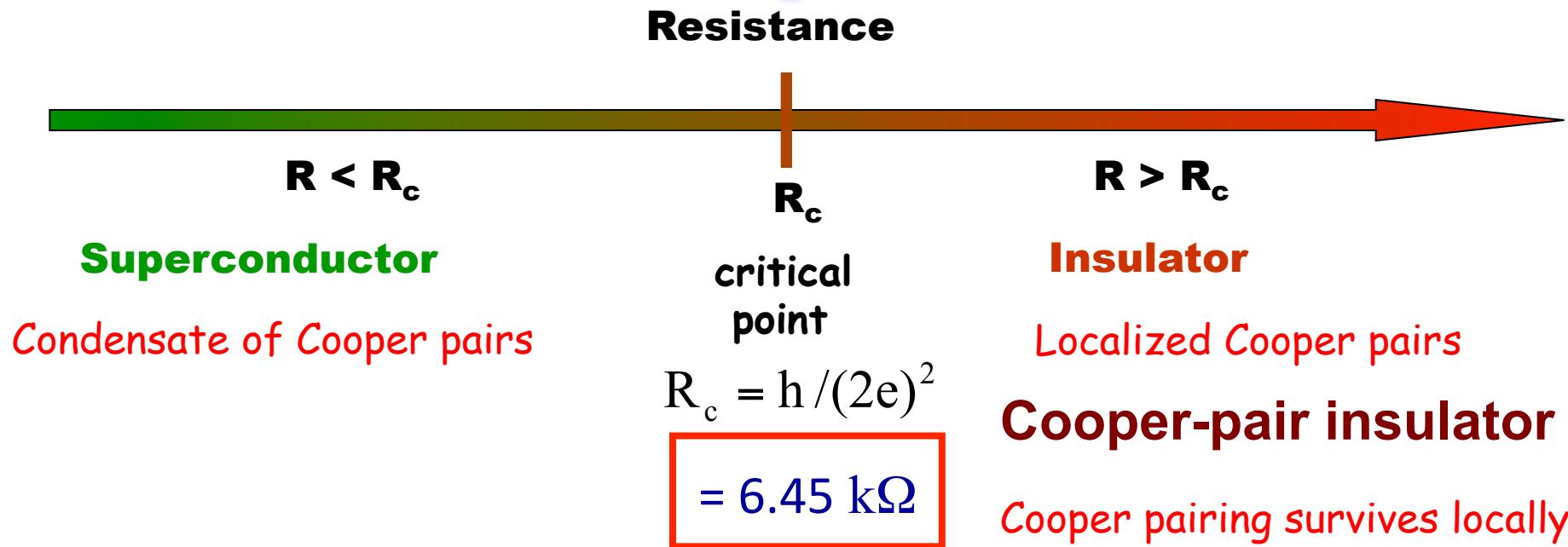
Bosonic mechanism

strong disorder

Bosonic mechanism

A. Gold, Z. Phys. B – Condensed Matter **52**, 1 (1983); Phys. Rev. A **33**, 652 (1986).
Matthew P.A. Fisher, G. Grinstein, S.M. Girvin , PRL **64**, 587 (1990).

control parameter



Superconductor – Insulator transition

weak disorder

Fermionic mechanism

Theory

S. Maekawa, H. Fukuyama, J. Phys. Soc. Jpn. 51, 1380 (1982).

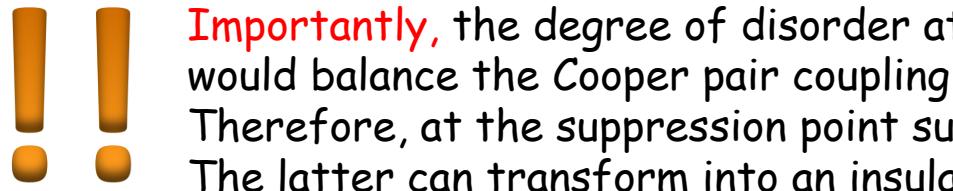
A.M. Finkelstein, JETP Lett. 45, 46 (1987)

The physical picture behind suppressing superconductivity by disorder:

- quasi-two-dimensional systems disorder inhibits electron mobility and thus impairs dynamic screening of the Coulomb interaction
- disorder enhances effects of the Coulomb repulsion between electrons which, if strong enough, breaks down Cooper pairing and destroys superconductivity

the decrease of the net attraction between electrons

the decrease of the transition temperature



Importantly, the degree of disorder at which the Coulomb repulsion would balance the Cooper pair coupling is not sufficient to localize normal carriers. Therefore, at the suppression point superconductors transforms into a metal. The latter can transform into an insulator upon further increase of disorder.

we can expect the following sequence of transitions

- Superconductor – Metal – Fermi-Insulator transition (**SMIT**)



Evolution of Superconductivity with Increasing Disorder in Two Dimensions

weak disorder

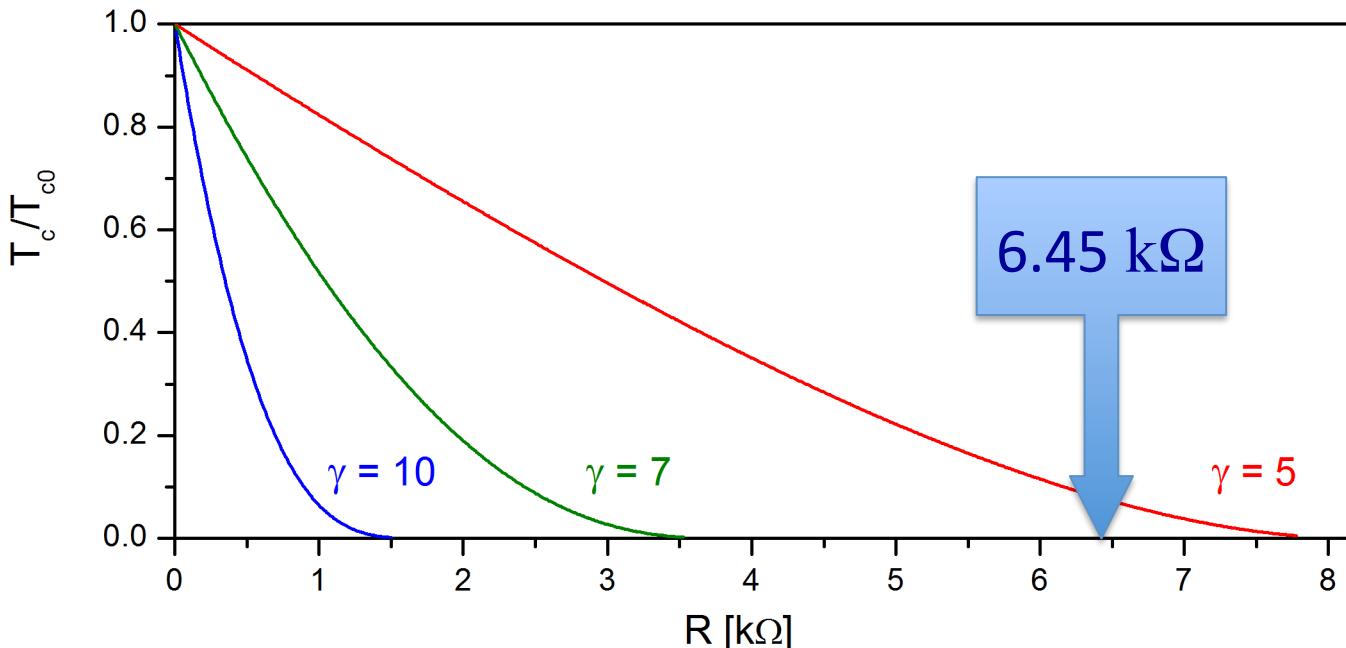
Fermionic mechanism

Theory

S. Maekawa, H. Fukuyama, J. Phys. Soc. Jpn. 51, 1380 (1982).

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$$T_c = \text{function } (R_{\square})$$



$$\ln\left(\frac{T_c}{T_{c0}}\right) = \gamma + \frac{1}{\sqrt{2r}} \ln\left(\frac{1/\gamma + r/4 - \sqrt{r/2}}{1/\gamma + r/4 + \sqrt{r/2}}\right)$$

$$r = R_{\square} e^2 / (2\pi^2 \hbar) \quad \gamma = \ln[\hbar/(k_B T_{c0} \tau)]$$

Vanishing of T_c is accompanied by vanishing of the amplitude of the superconductive order parameter Δ (!)

Evolution of Superconductivity with Increasing Disorder in Two Dimensions

Fermionic mechanism

- Superconductor – Metal – Fermi-Insulator transition (**SMIT**)



Different bordering states

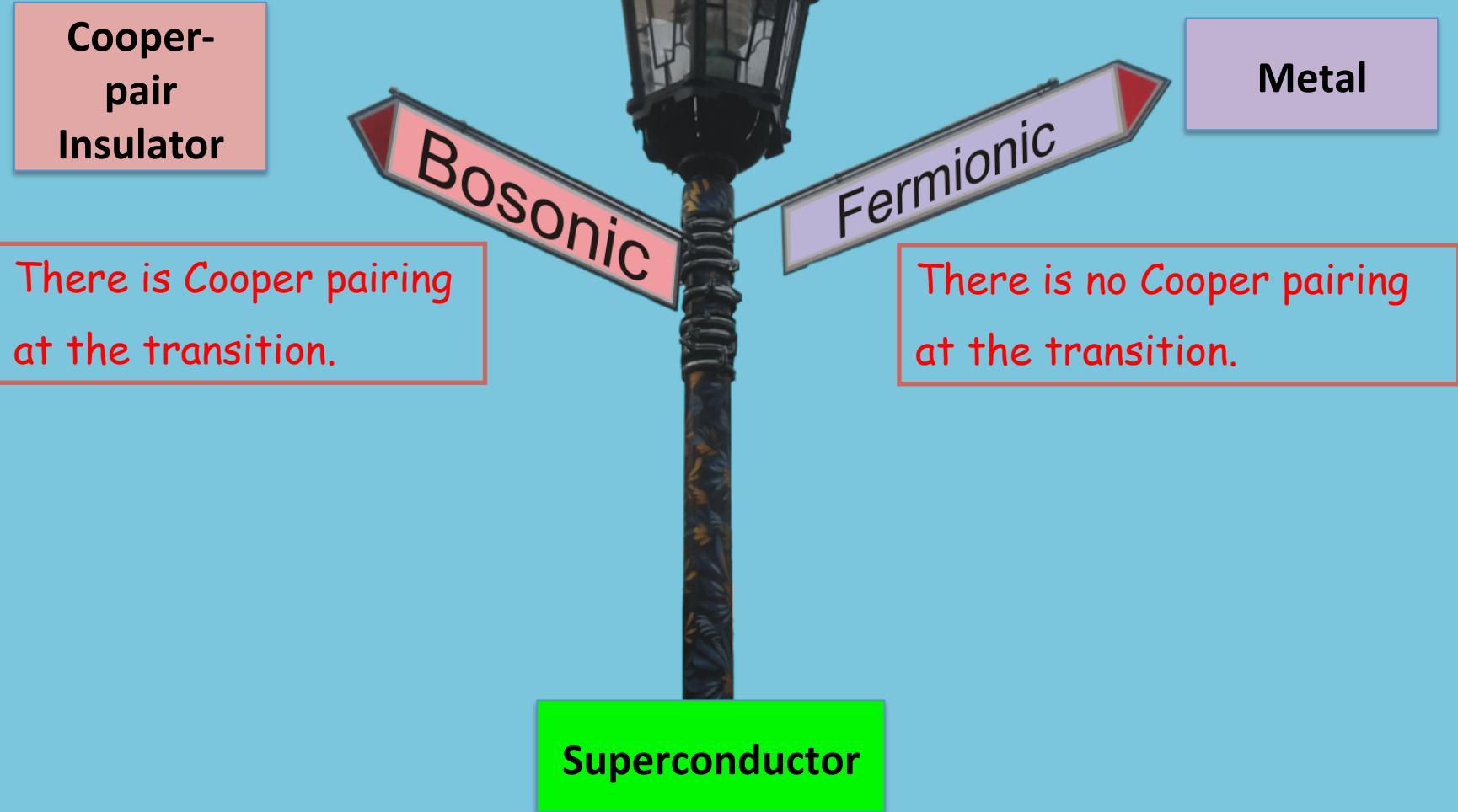
Bosonic mechanism

Cooper-pair insulator

- Superconductor – Bose-Insulator transition (**SIT**)



SIT or SMIT



Evolution of Superconductivity with Increasing Disorder in Two Dimensions

Main questions:

to which degree the transport data can be conclusive in favoring one or another scenario

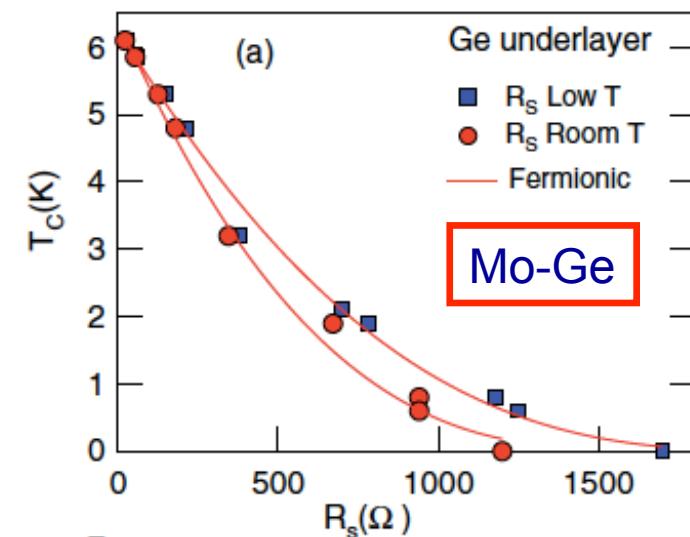
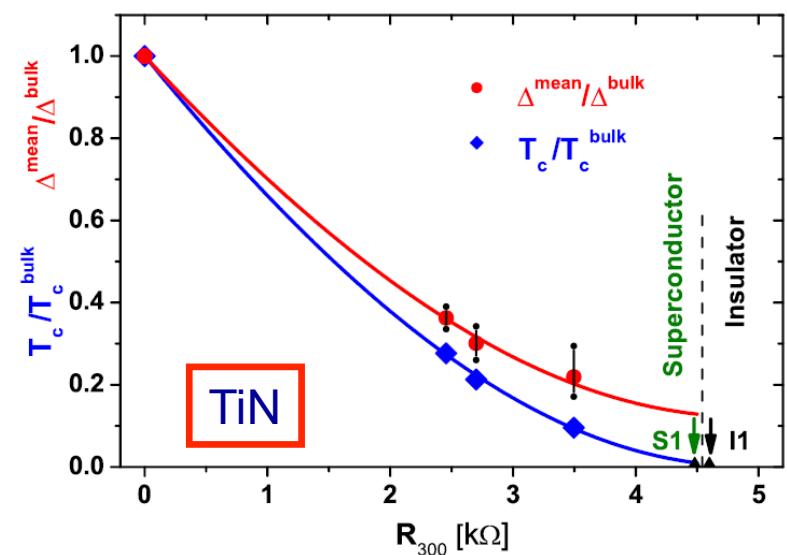
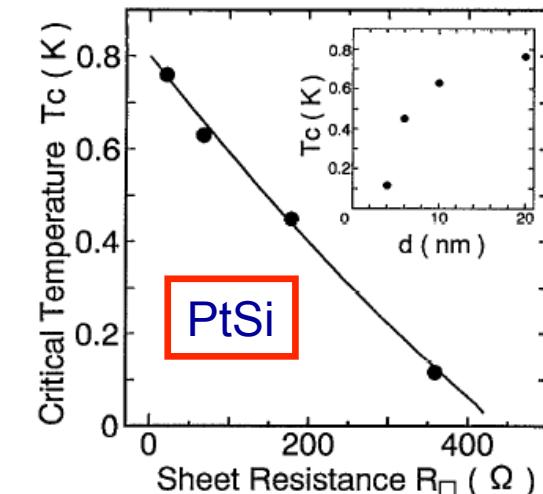
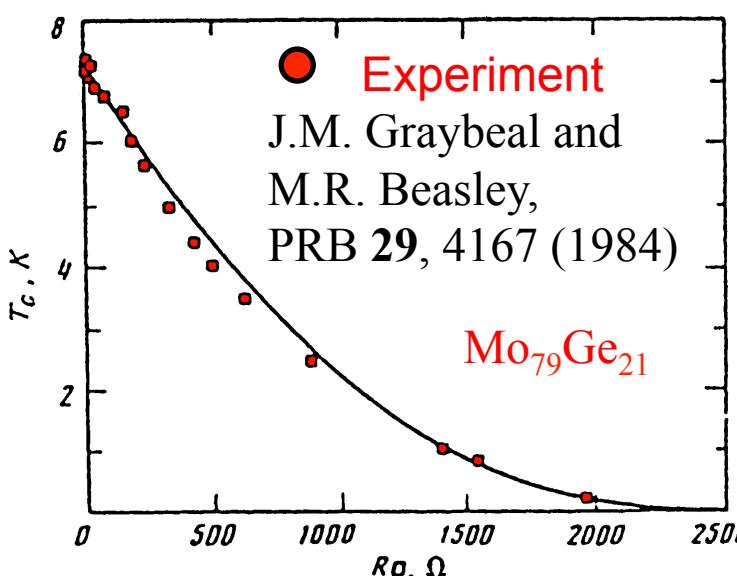
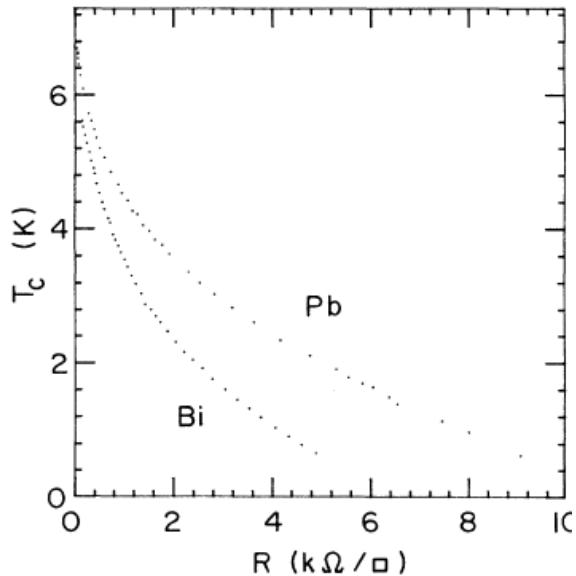
which criteria for the proper choice are available at present

SIT or SMIT

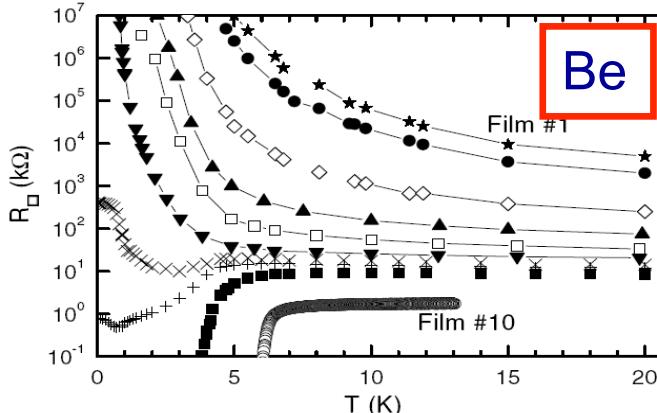
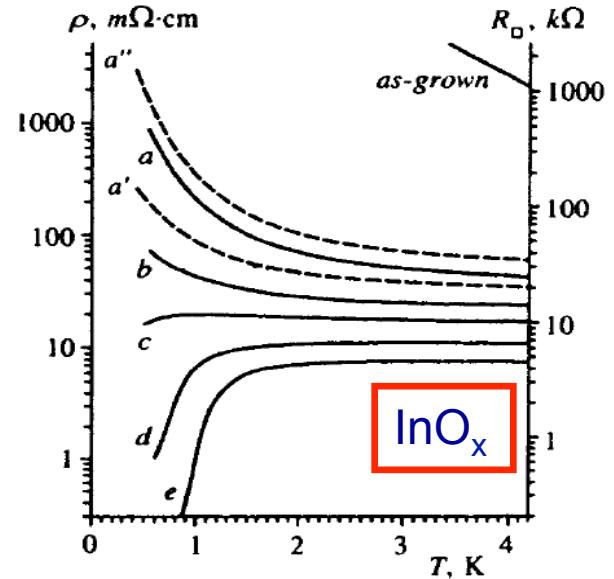
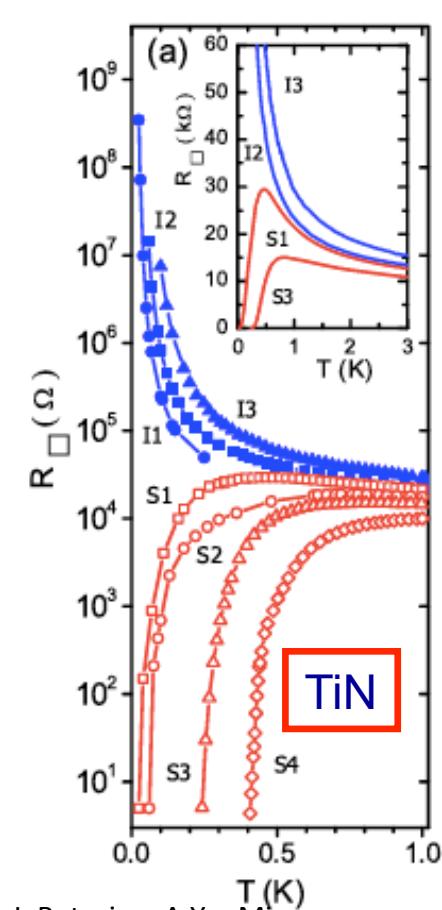
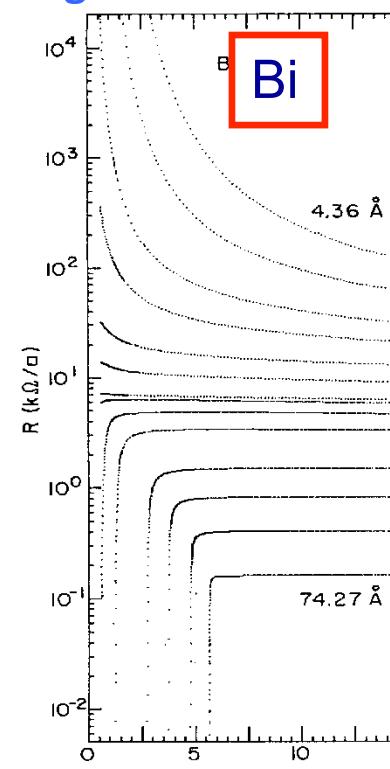
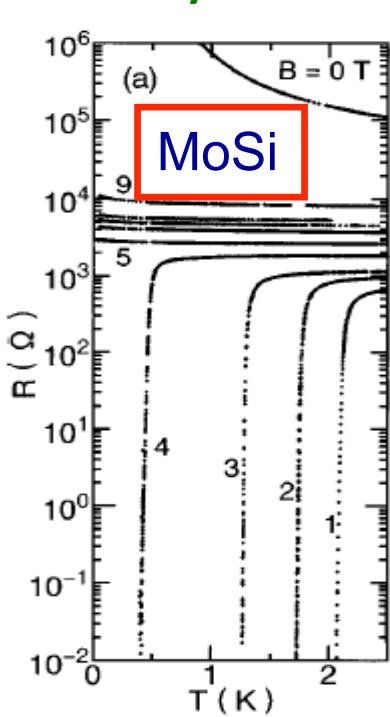
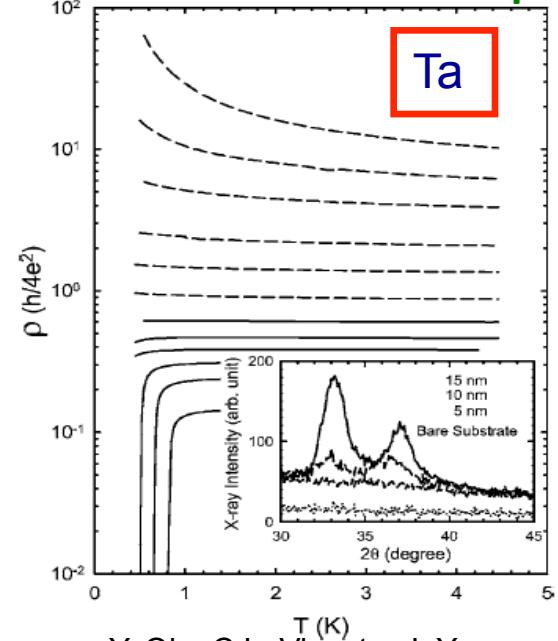


We can claim
that we do understand something,
if we, basing on this understanding,
can predict something else.

Evolution of Superconductivity with Increasing Disorder in Two Dimensions



Evolution of Superconductivity with Increasing Disorder in Two Dimensions



to which degree the transport data can be conclusive in favoring one or another scenario?

TERMINOLOGY

While in the literature the term “insulator” and/or “the insulating state” is often used to characterize the materials that exhibit negative dR/dT , we find this terminology confusing and misleading:

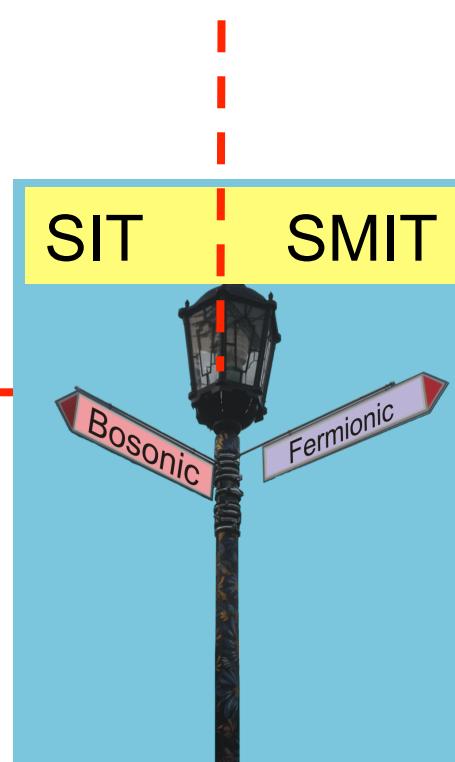
It ignores the very purpose of the terms “metallic” and “insulating”: To discriminate between the different physical mechanisms of conductivity.

insulator

thermally activated
or Mott-Efros-Shklovskii-like
behavior of conductivity

metal

Drude conductivity
+
quantum contributions

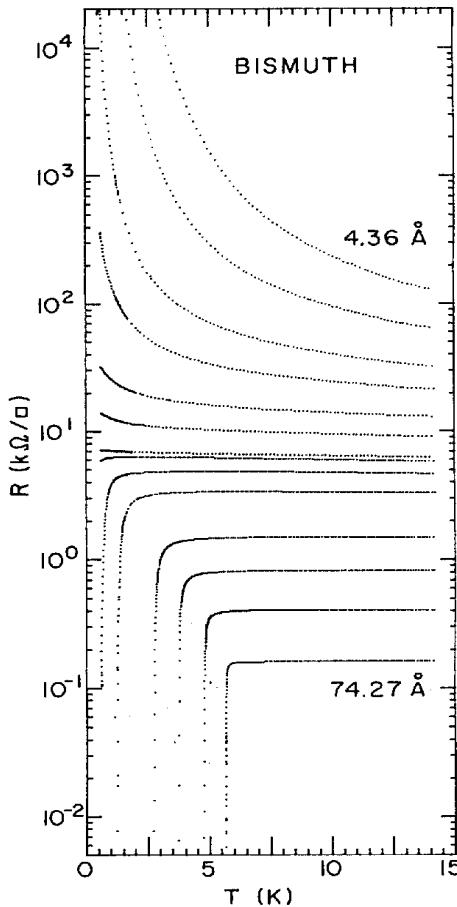


Evolution of Superconductivity with Increasing Disorder in Two Dimensions

negative dR/dT

Is it conclusive for the choice of the state?

$$R_c = h/(2e)^2$$



Does the universal resistance for SIT exist?

Fan-shaped curves

D.V. Haviland, Y. Liu, and A.M. Goldman, PRL 62, 2180 (1989)

$d < d_c$ Insulator

d_c Metal

$d > d_c$ Superconductor

Bi films
 $R_c = 6.45 \text{ k}\Omega$

The onset of superconductivity in homogeneous ultrathin films is found to occur when their normal-state sheet resistance falls below a value close to $h/4e^2$, the quantum resistance for pairs. The data fur-

Evolution of Superconductivity with Increasing Disorder in Two Dimensions

negative dR/dT

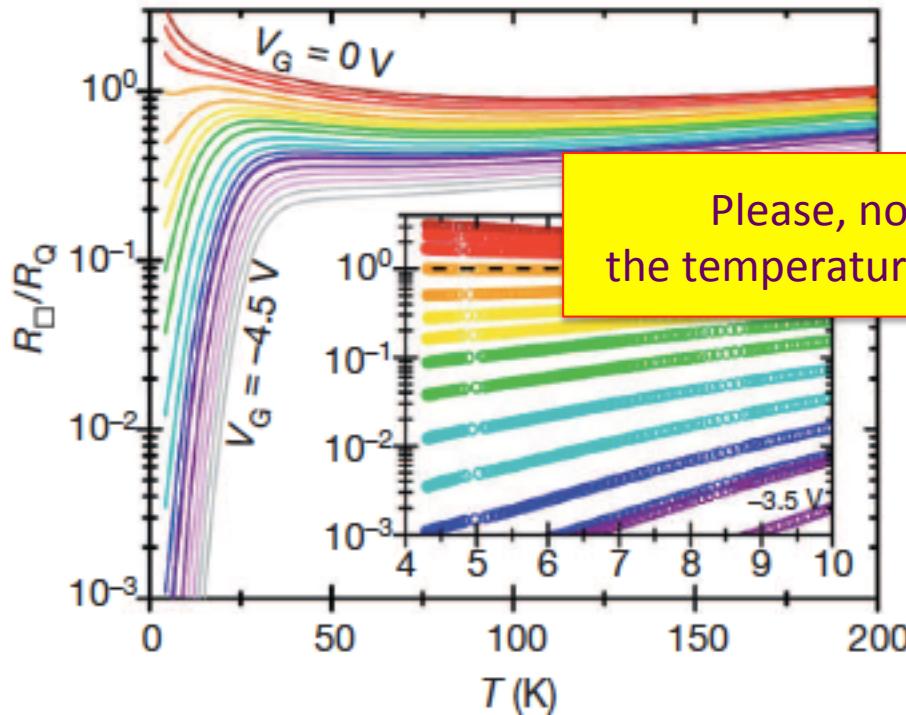
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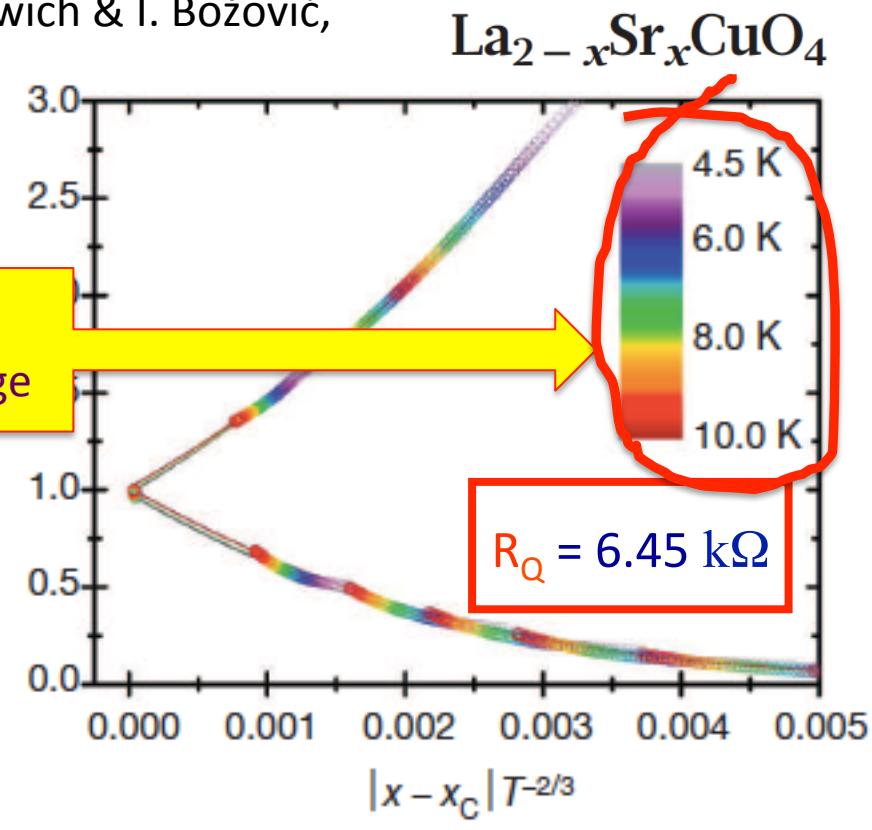
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Fan-shaped curves + scaling

A. T. Bollinger, G. Dubuis, J. Yoon, D. Pavuna, J. Misewich & I. Božović,
Nature 472, 458 (2011)



Please, note
the temperature range



Evolution of Superconductivity with Increasing Disorder in Two Dimensions

negative dR/dT

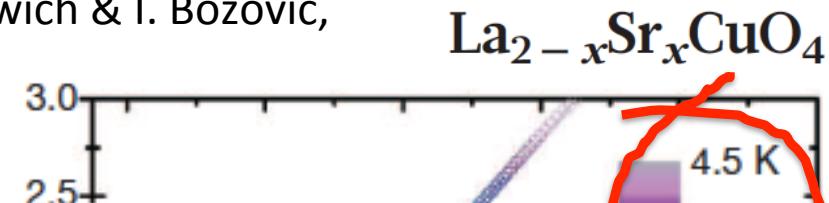
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Nature 472, 458 (2011)



Hundreds of resistance versus temperature and carrier density curves were recorded and shown to collapse onto a single function, as predicted for a two-dimensional superconductor-insulator transition¹¹⁻¹⁴. The observed critical resistance is precisely the quantum resistance for pairs, $R_Q = h/(2e)^2 = 6.45 \text{ k}\Omega$, suggestive of a phase transition driven by quantum phase fluctuations, and Cooper pair (de)localization.

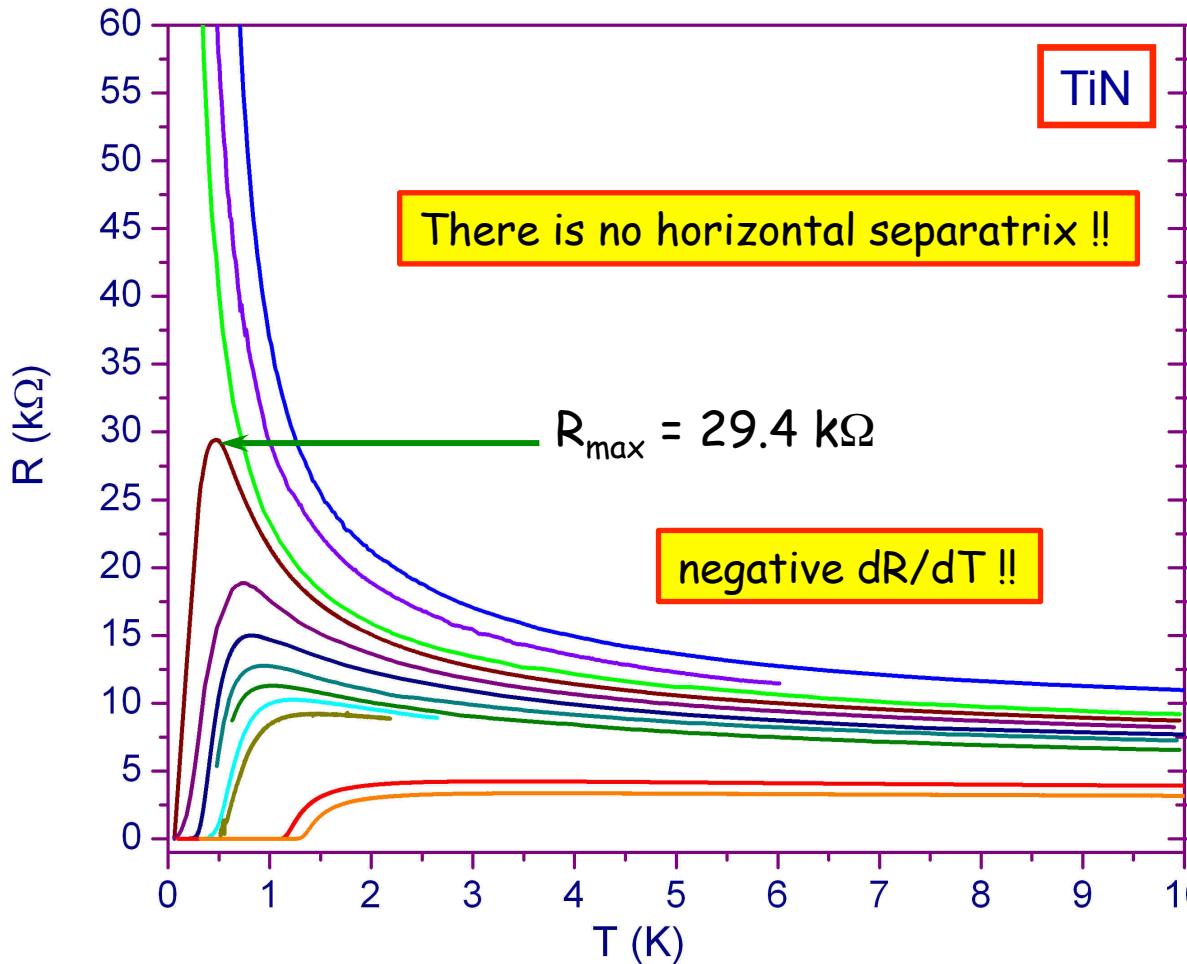
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negative dR/dT

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Does the universal resistance for SIT exist?



R_{sq} @ 300 K

4.60 kΩ – I1

4.48 kΩ - S1

<3% (!)

T. Baturina, D.R. Islamov, J. Bentner, C. Strunk, M.R. Baklanov, A. Satta, JETP Lett. 79, 337 (2004)

T. Baturina, C. Strunk, M.R. Baklanov, A. Satta, PRL 98, 127003 (2007)

T. Baturina, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk, PRL 99, 257003 (2007)

T. Baturina, A. Bilušić, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk, Physica C 468, 316 (2008)

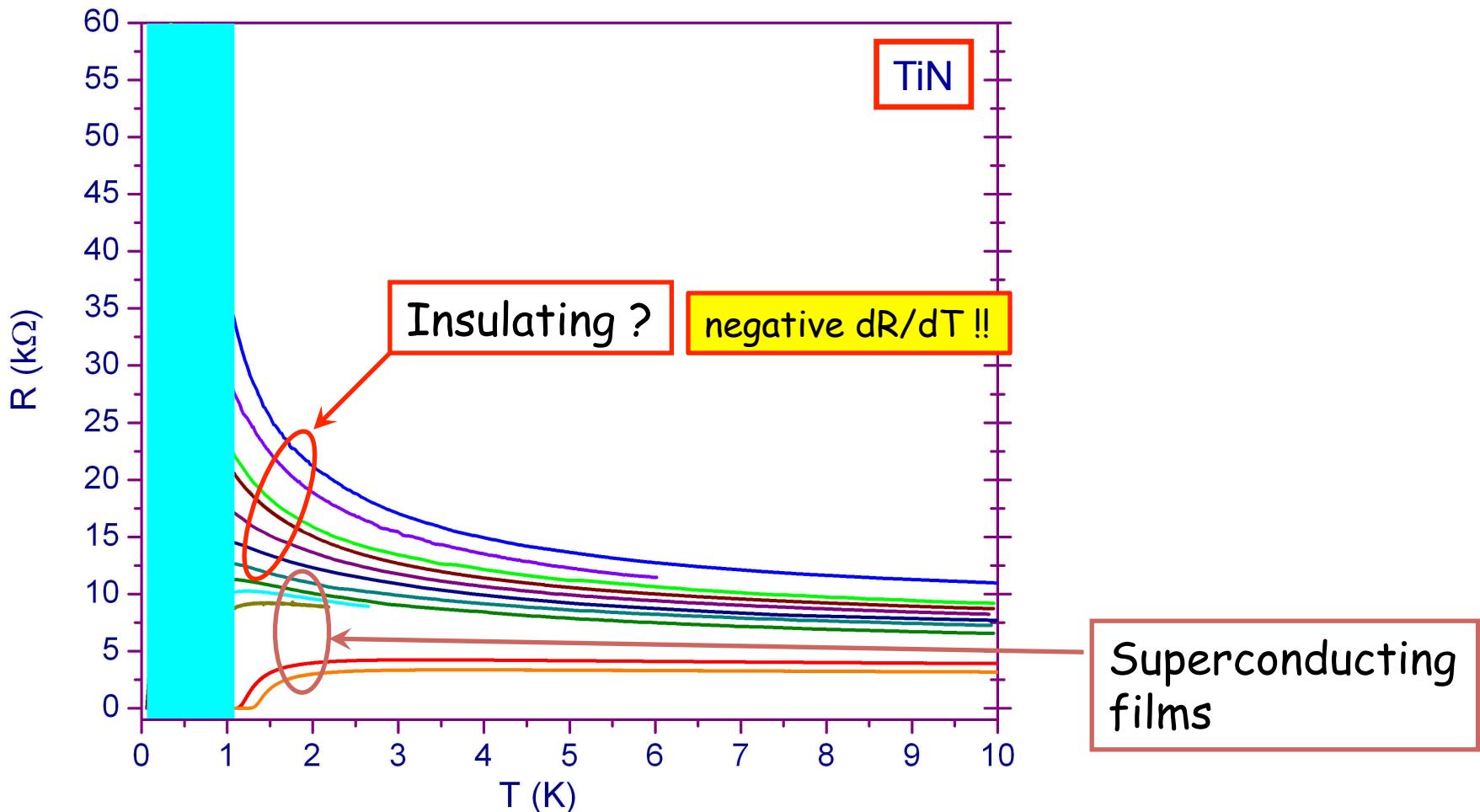
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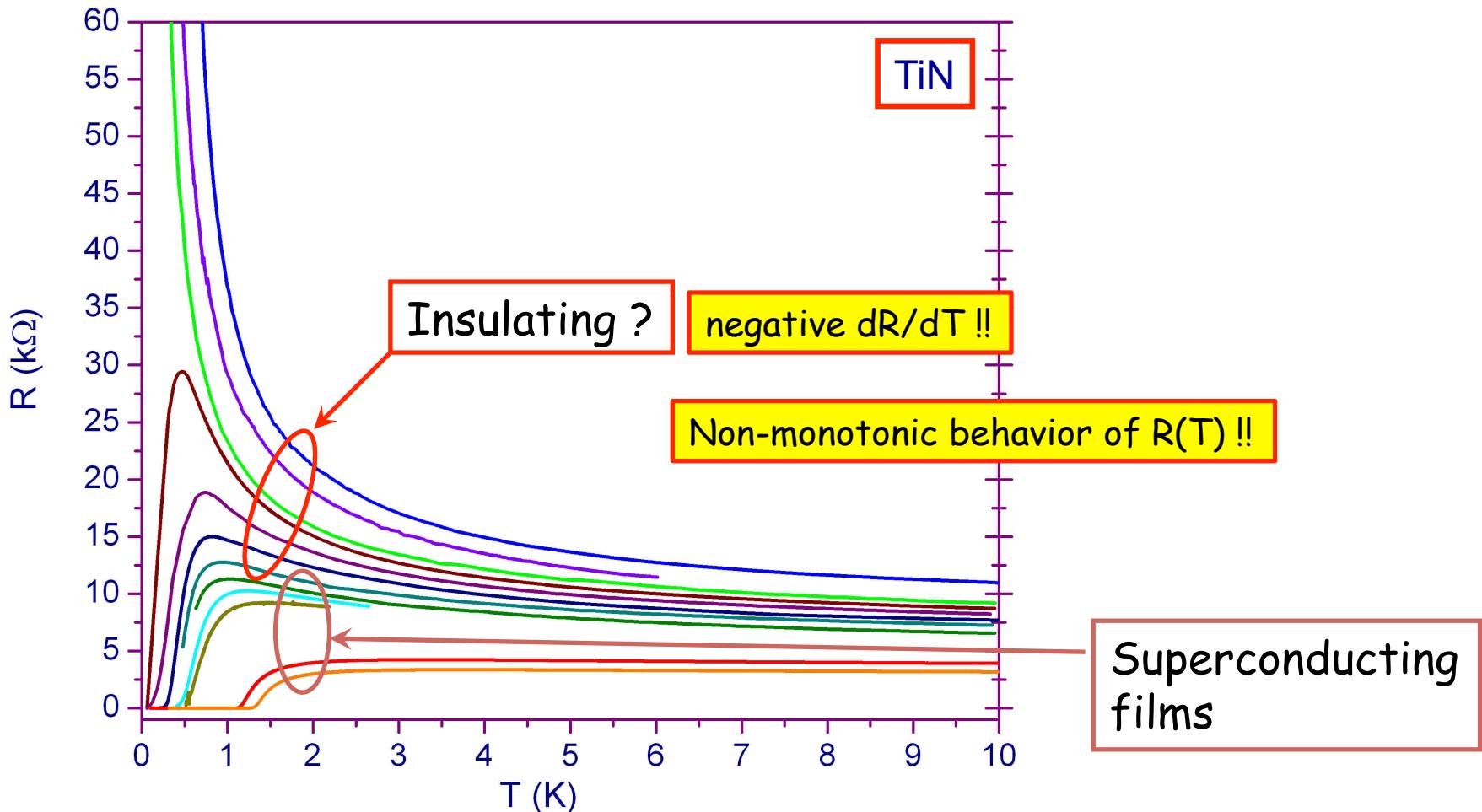
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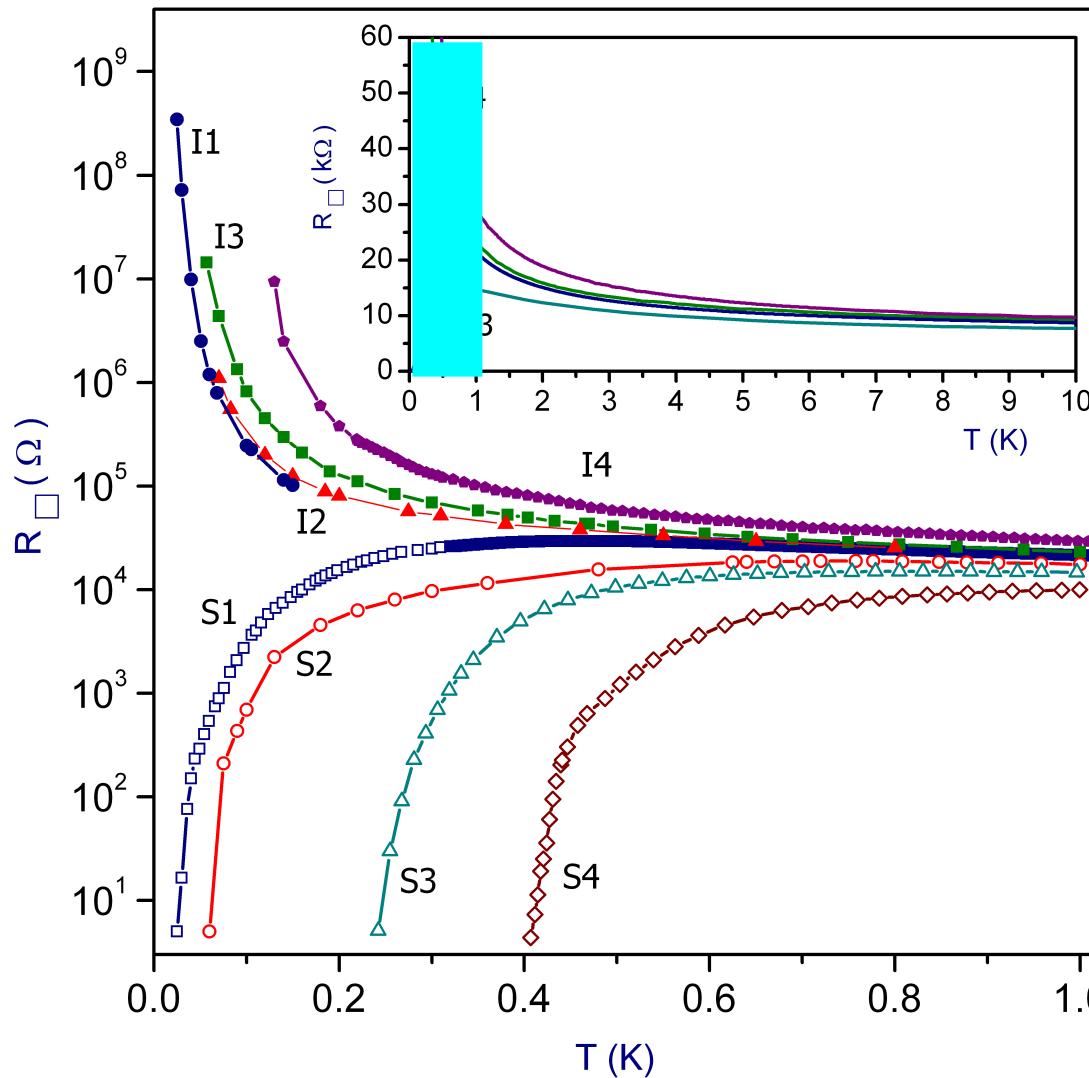
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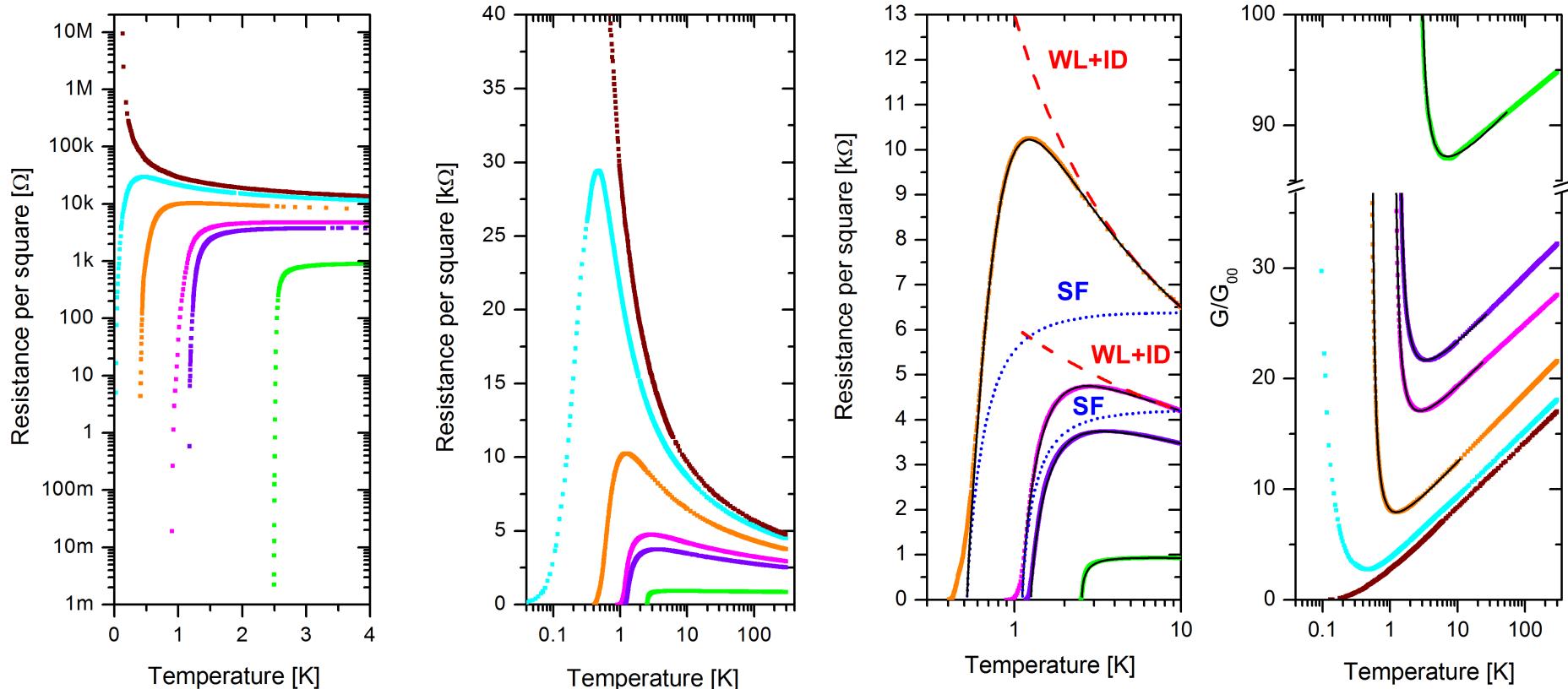


T. Baturina, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk, PRL 99, 257003 (2007)

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Evolution of Superconductivity with Increasing Disorder in Two Dimensions

Non-monotonic behavior of $R(T)$!!



Drude conductivity
+

quantum contributions: weak localization, e-e interaction, superconducting fluctuations

$$R^{-1} = G_0 + \Delta G^{WL+ID} + \Delta G^{SF}$$

Quantum contributions to conductivity

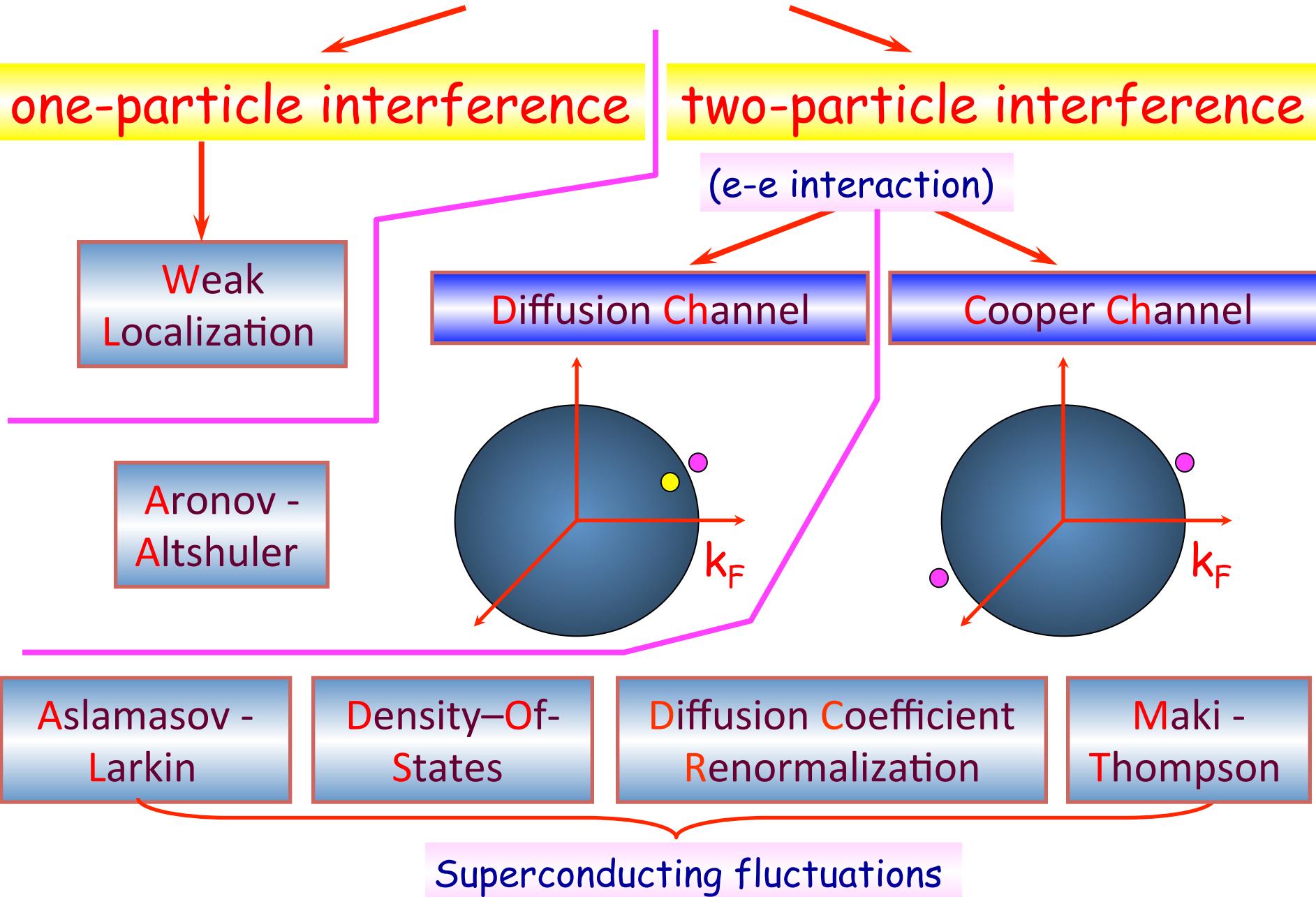
It is firmly established that the low-temperature behavior of the resistance $R(T,B)$ of quasi-two-dimensional systems as well as tunneling conductivity is governed by quantum contributions to conductivity.

Reviews:

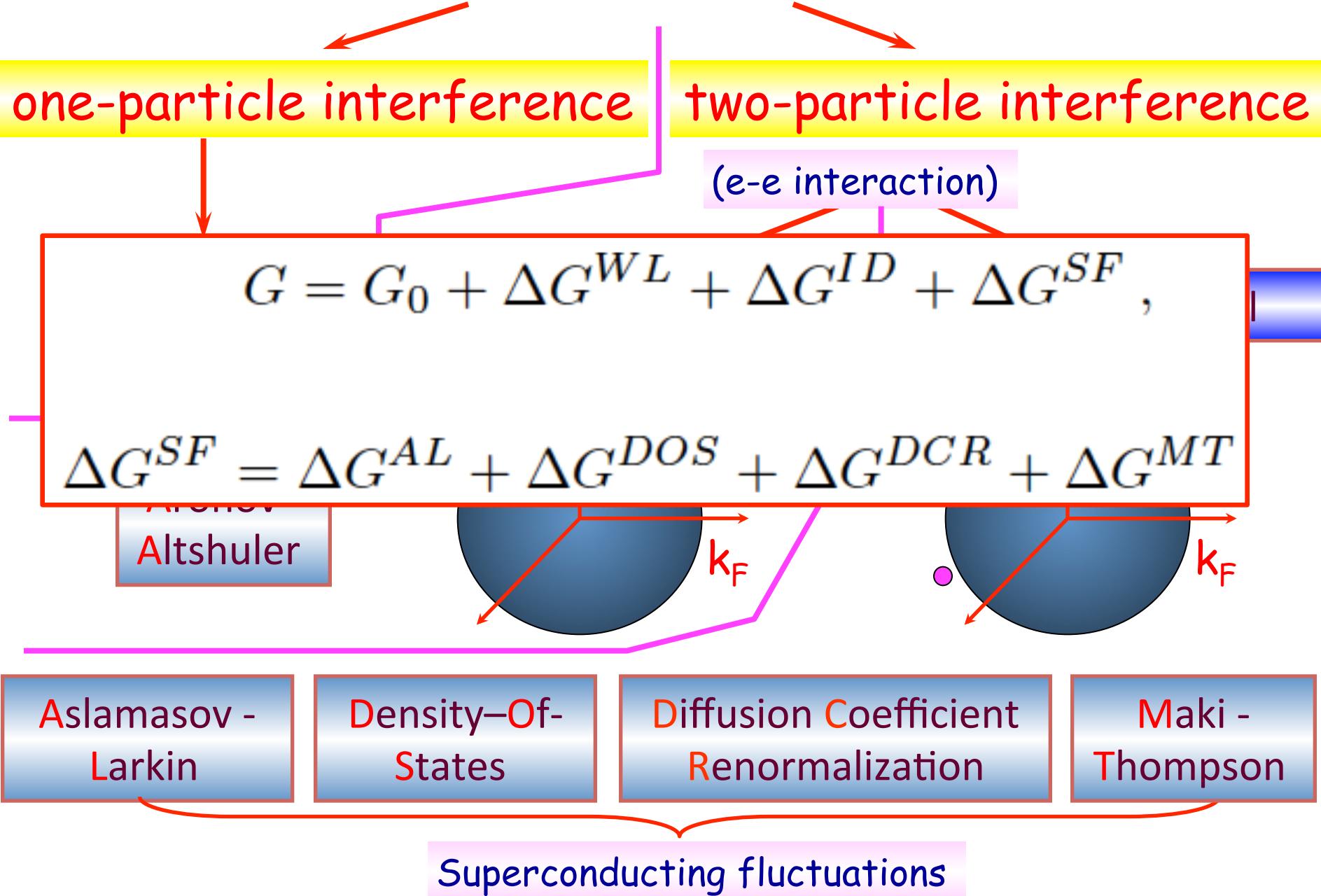
- B. L. Altshuler and A. G. Aronov, in *Electron-Electron Interactions in Disordered Systems* (eds A. L. Efros, M. Pollak) (North-Holland, 1985).
- A. Larkin and A. Varlamov, in *Theory Of Fluctuations In Superconductors* (Clarendon, 2005).

-
- A. Glatz, A. A. Varlamov, and V. M. Vinokur, EPL 94, 47005 (2011)
A. Glatz, A. A. Varlamov, and V. M. Vinokur, PRB 84, 104510 (2011)

Quantum contributions to conductivity



Quantum contributions to conductivity



Quantum contributions to conductance

quasi-2D

Conductance = 1/[Resistance per square]

$R(T)$ at $B = 0$

Weak
Localization (WL)

$$\frac{\Delta G^{WL}(T)}{G_{00}} = \alpha p \ln \left(\frac{kT\tau}{\hbar} \right) \quad \begin{aligned} \alpha &= 1, & \text{if } \tau_\varphi << \tau_{so} \\ \alpha &= -1/2, & \text{if } \tau_\varphi >> \tau_{so} \end{aligned}$$

$$\tau_\varphi \propto T^{-p}$$

Aronov -
Altshuler (ID)

$$\frac{\Delta G^{ID}(T)}{G_{00}} = \left[4 - 3 \frac{2+F}{F} \ln \left(1 + \frac{F}{2} \right) \right] \ln \left(\frac{kT\tau}{\hbar} \right)$$

$$\boxed{\frac{\Delta G^{WL+ID}(T)}{G_{00}} = A \ln \left(\frac{kT\tau}{\hbar} \right)}$$

$$G_{00} = e^2 / (2\pi^2 \hbar) \approx (81 \text{ k}\Omega)^{-1}$$

Quantum contributions to conductance

$R(T)$ at $B = 0$

Weak
Localization (WL)

Aronov -
Altshuler (ID)

$$\frac{\Delta G^{WL+ID}(T)}{G_{00}} = A \ln \left(\frac{kT\tau}{\hbar} \right)$$

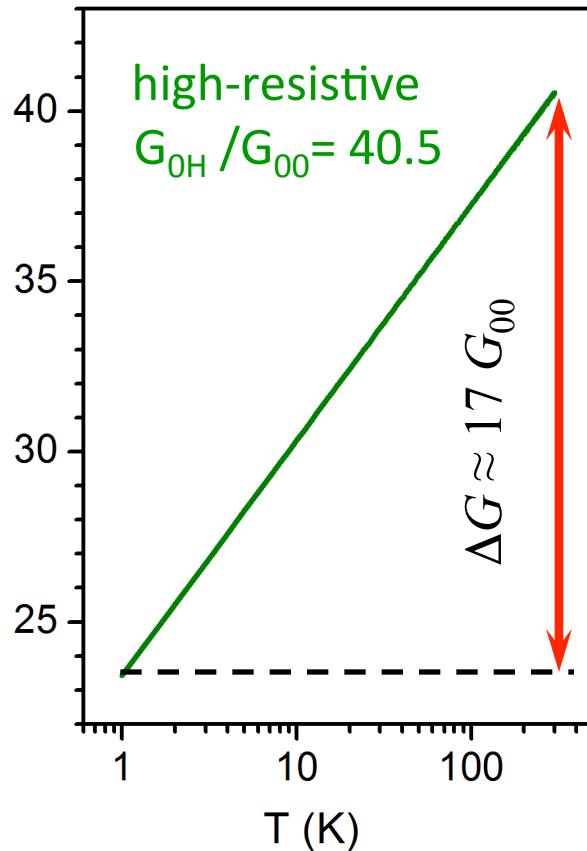
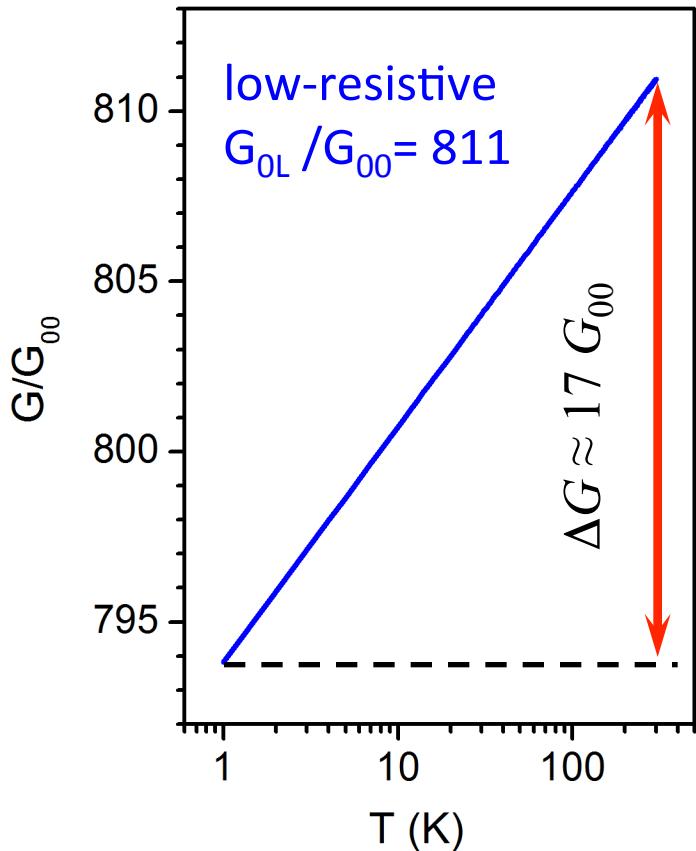
How does it work:

$$@ 300 \text{ K} \quad R_L = 100 \Omega$$

$$R_H = 2000 \Omega$$

$$G_{00} \approx (81 \text{ k}\Omega)^{-1}$$

$$G(T) = G_0 + AG_{00} \ln(T/300)$$



$$G_0 = 1/R \text{ (300 K)}$$

$$A = 3$$

Quantum contributions to conductance

$R(T)$ at $B = 0$

Weak
Localization (WL)

+

Aronov -
Altshuler (ID)

=

$$\frac{\Delta G^{WL+ID}(T)}{G_{00}} = A \ln \left(\frac{kT\tau}{\hbar} \right)$$

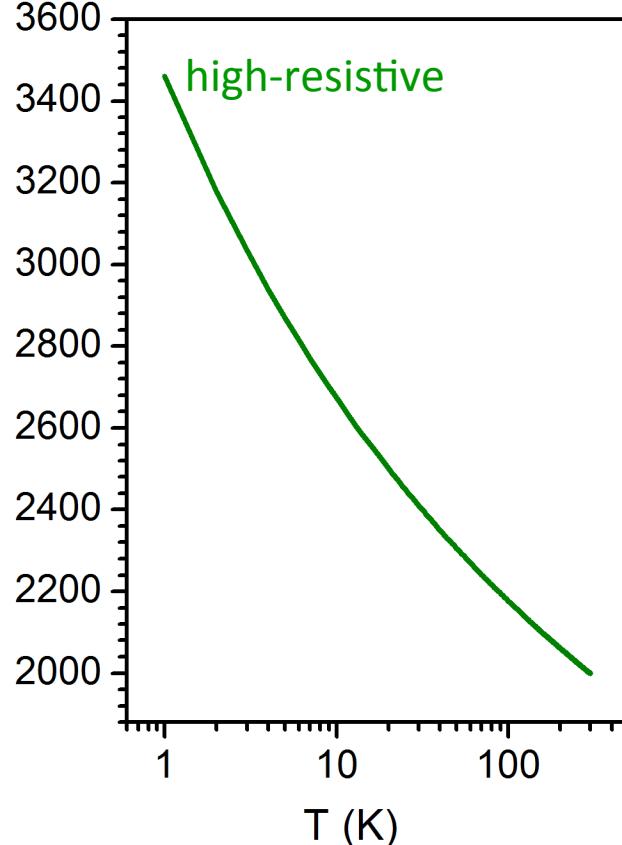
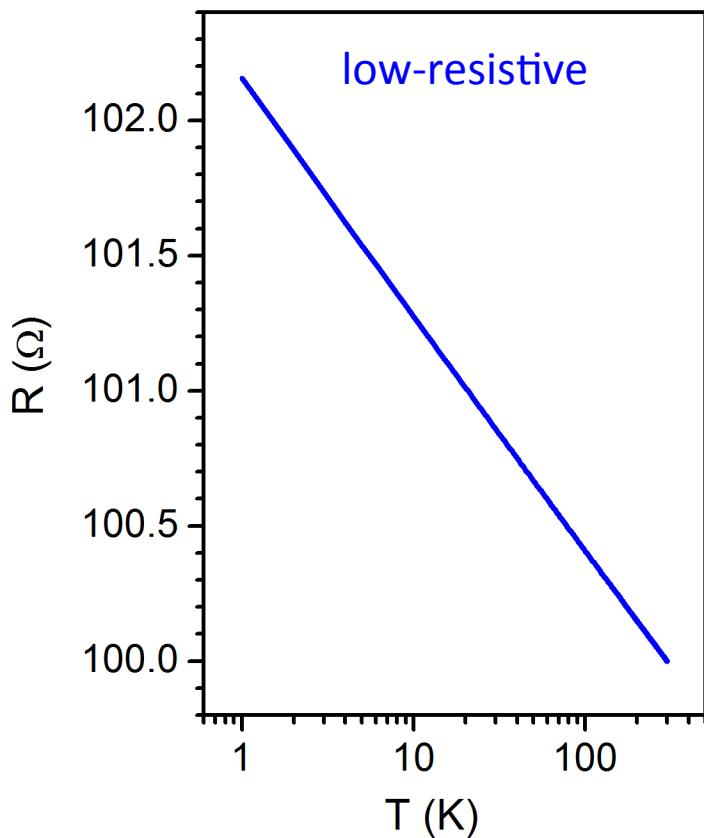
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$$G_0 = 1/R \text{ (300 K)}$$

$$A=3$$

$$R(T) = 1/G(T)$$

$$\frac{\Delta R}{R} \approx \frac{\Delta G}{G}$$

$$\Delta R \approx R^2 \Delta G$$

Quantum contributions to conductance

$R(T)$ at $B = 0$

Weak Localization (WL)

+

Aronov - Altshuler (ID)

=

$$\frac{\Delta G^{WL+ID}(T)}{G_{00}} = A \ln \left(\frac{kT\tau}{\hbar} \right)$$

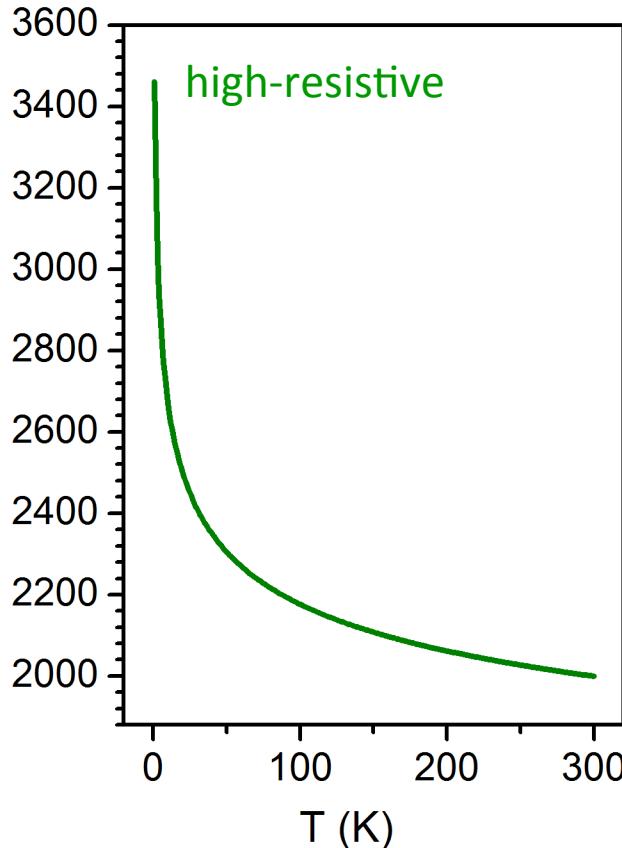
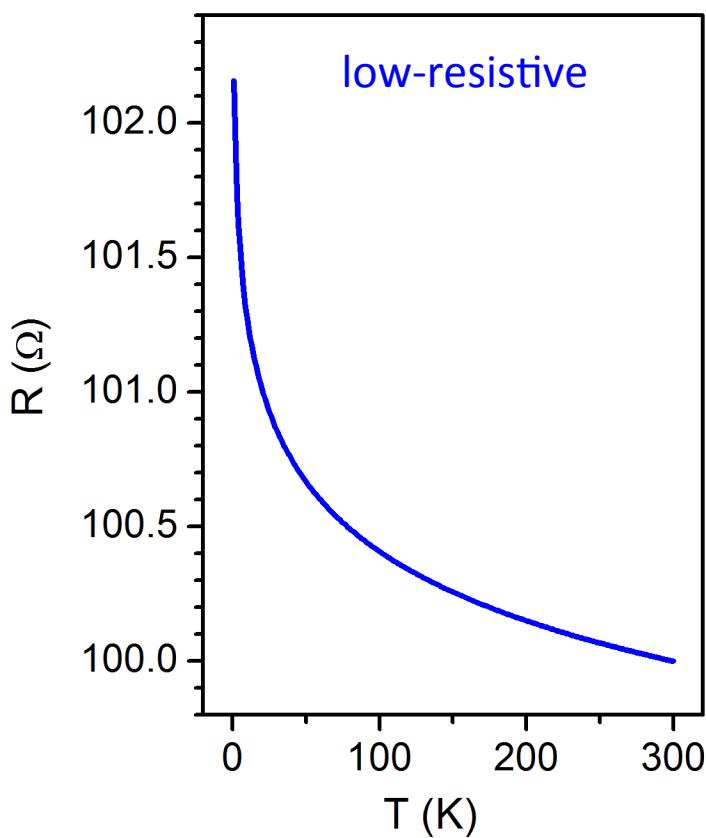
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$$G_0 = 1/R \text{ (300 K)}$$

$$A = 3$$

$$R(T) = 1/G(T)$$

$$\frac{\Delta R}{R} \approx \frac{\Delta G}{G}$$

$$\Delta R \approx R^2 \Delta G$$

Quantum corrections to conductivity

$R(T)$ at $B = 0$

Weak
Localization (WL)

+

Aronov -
Altshuler (ID)

=

$$\frac{\Delta G^{WL+ID}(T)}{G_{00}} = A \ln \left(\frac{kT\tau}{\hbar} \right)$$

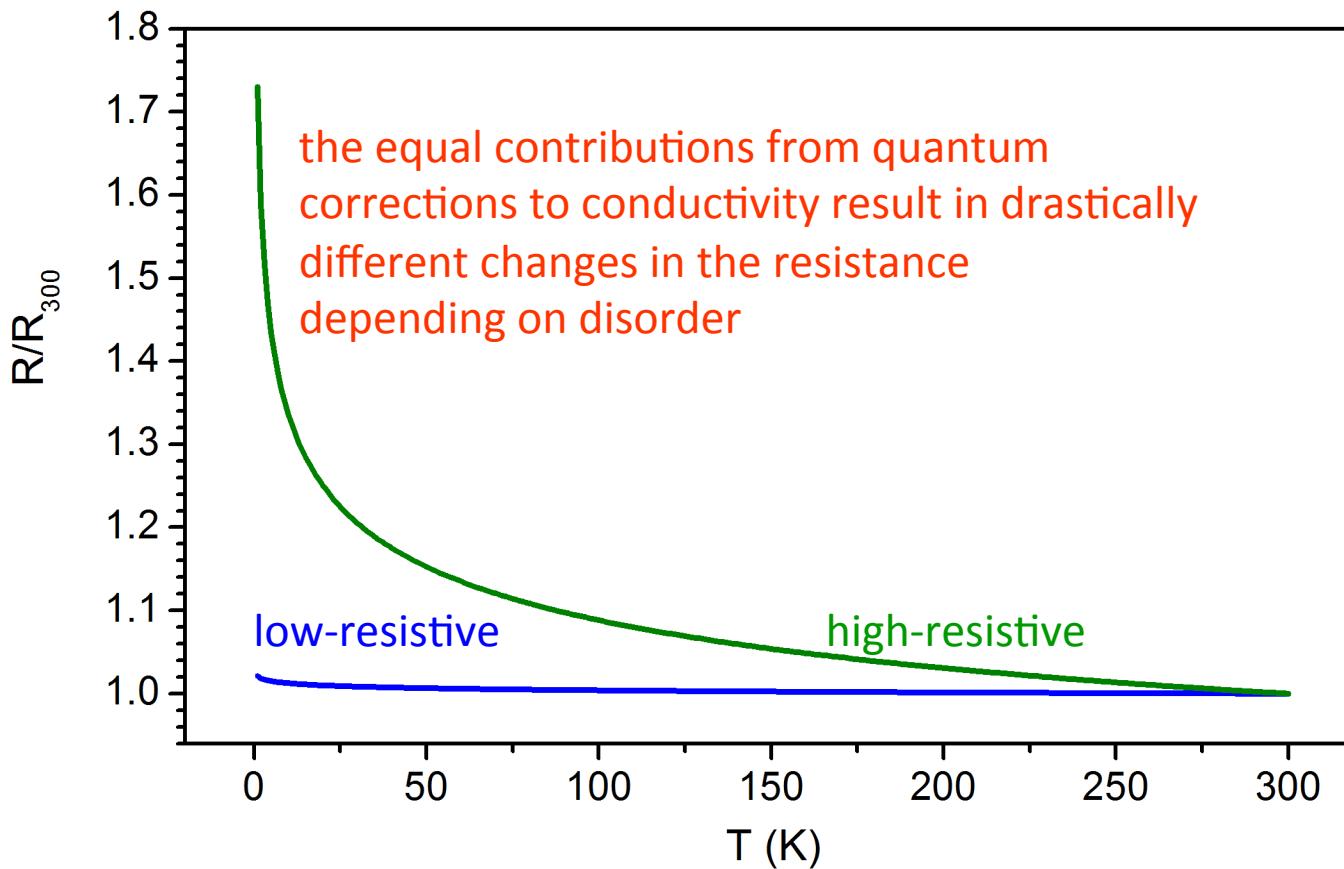
How does it work:

$$@ 300 \text{ K} \quad R_L = 100 \Omega$$

$$R_H = 2000 \Omega$$

$$G_{00} \approx (81 \text{ k}\Omega)^{-1}$$

$$G(T) = G_0 + AG_{00} \ln(T/300)$$



$$G_0 = R(300 \text{ K})$$

$$A = 3$$

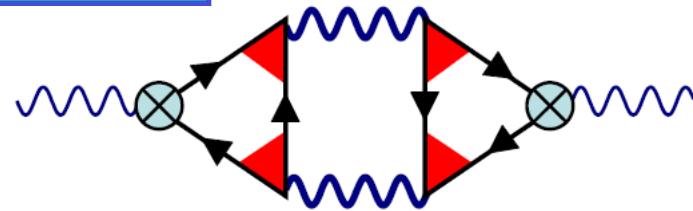
$$R(T) = 1/G(T)$$

$$\frac{\Delta R}{R} \approx \frac{\Delta G}{G}$$

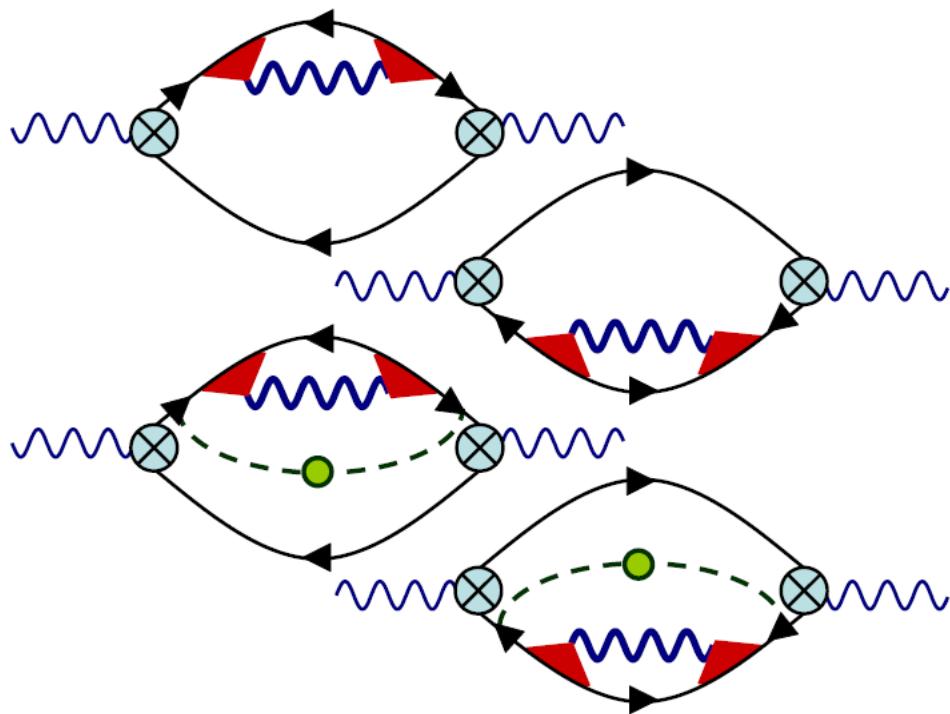
$$\Delta R \approx R^2 \Delta G$$

Cooper Channel

Aslamasov -
Larkin (**AL**)

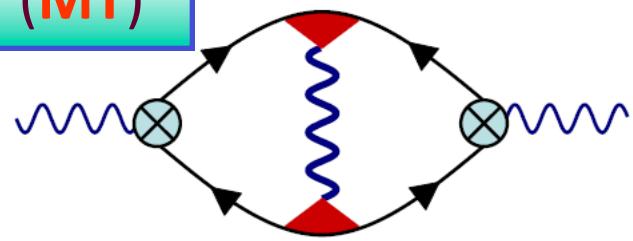


Density–Of–
States (**DOS**)

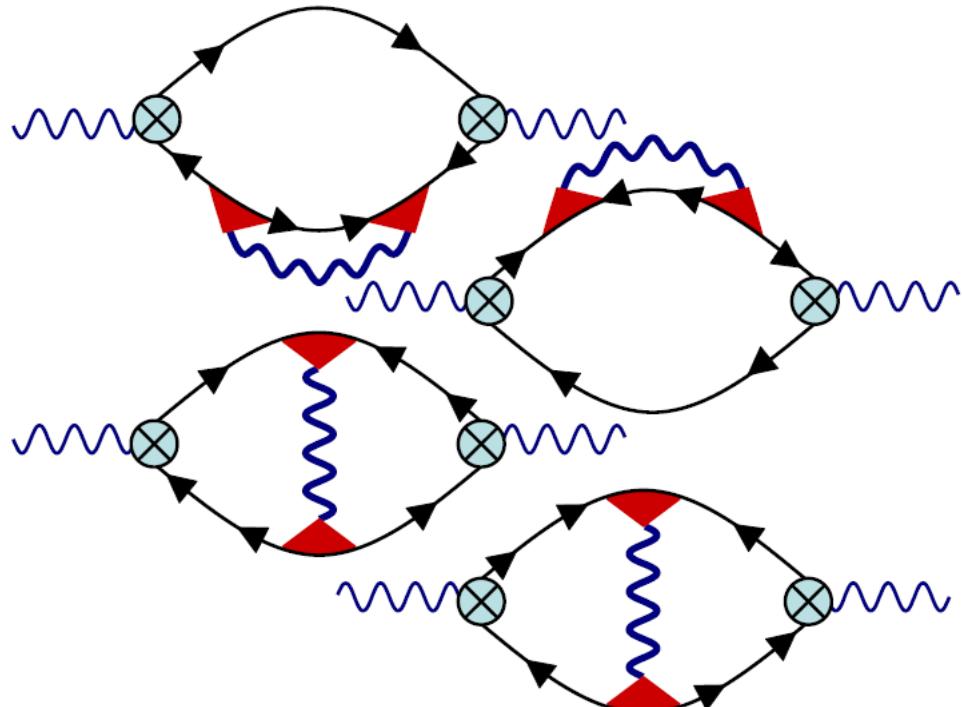


Superconducting fluctuations

Maki -
Thompson (**MT**)



Diffusion Coefficient
Renormalization (**DCR**)



$$\delta\sigma_{xx}^{\text{AL}} = \underbrace{\frac{e^2}{\pi} \sum_{m=0}^{\infty} (m+1) \int_{-\infty}^{\infty} \frac{dx}{\sinh^2 \pi x} \left\{ \frac{[\text{Re}^2 (\mathcal{E}_m - \mathcal{E}_{m+1}) - \text{Im}^2 (\mathcal{E}_m - \mathcal{E}_{m+1})] \text{Im } \mathcal{E}_m \text{Im } \mathcal{E}_{m+1}}{|\mathcal{E}_m|^2 |\mathcal{E}_{m+1}|^2} \right.}_{\delta\sigma_{xx}^{\text{AL}}} + \\ \left. \underbrace{- \frac{\text{Re} (\mathcal{E}_m - \mathcal{E}_{m+1}) \text{Im} (\mathcal{E}_m - \mathcal{E}_{m+1}) (\text{Im } \mathcal{E}_m \text{Re } \mathcal{E}_{m+1} + \text{Im } \mathcal{E}_{m+1} \text{Re } \mathcal{E}_m)}{|\mathcal{E}_m|^2 |\mathcal{E}_{m+1}|^2} \right\}, \\ + \delta\sigma_{xx}^{\text{AL}}$$

$$\delta\sigma_{xx}^{\text{MT}} = \frac{e^2}{\pi} \left(\frac{h}{t} \right) \sum_{m=0}^M \underbrace{\frac{1}{\gamma_\phi + \frac{2h}{t} (m+1/2)} \int_{-\infty}^{\infty} \frac{dx}{\sinh^2 \pi x} \frac{\text{Im}^2 \mathcal{E}_m}{|\mathcal{E}_m|^2}}_{\delta\sigma_{xx}^{\text{MT(an)}} + \delta\sigma_{xx}^{\text{MT(reg2)}}} + \underbrace{\frac{e^2}{\pi^4} \left(\frac{h}{t} \right) \sum_{m=0}^M \sum_{k=-\infty}^{\infty} \frac{4\mathcal{E}_m''(t, h, |k|)}{\mathcal{E}_m(t, h, |k|)}}_{\delta\sigma_{xx}^{\text{MT(reg1)}}},$$

$$\delta\sigma_{xx}^{\text{DOS}} = \frac{4e^2}{\pi^3} \left(\frac{h}{t} \right) \sum_{m=0}^M \int_{-\infty}^{\infty} \frac{dx}{\sinh^2 \pi x} \frac{\text{Im } \mathcal{E}_m \text{Im } \mathcal{E}'_m}{|\mathcal{E}_m|^2}, \quad \delta\sigma_{xx}^{\text{DCR}} = \frac{4e^2}{3\pi^6} \left(\frac{h}{t} \right)^2 \sum_{m=0}^M \left(m + \frac{1}{2} \right) \sum_{k=-\infty}^{\infty} \frac{8\mathcal{E}_m'''(t, h, |k|)}{\mathcal{E}_m(t, h, |k|)}.$$

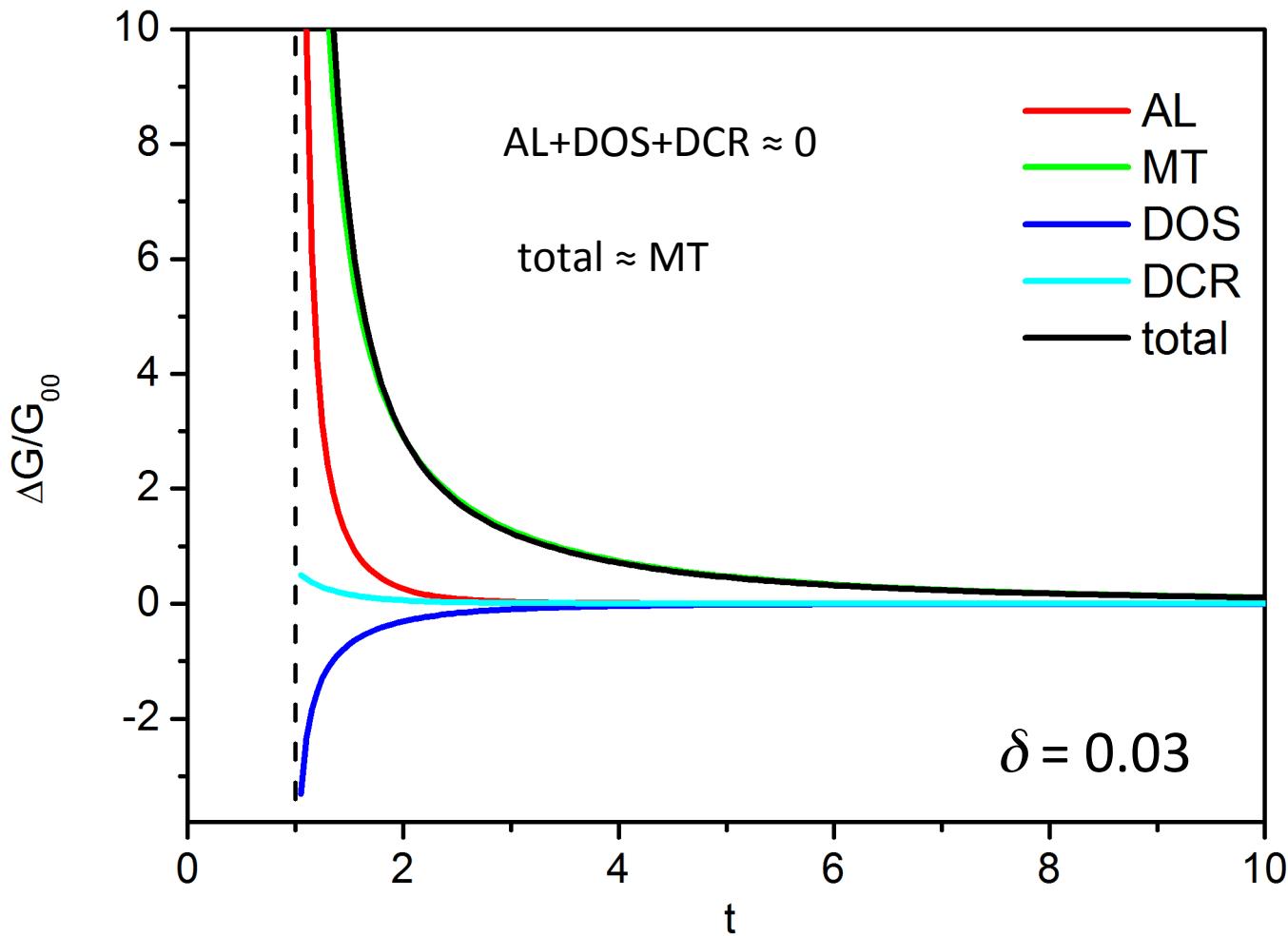
$$h = \frac{\pi^2}{8\gamma_E} \frac{H}{H_{c2}(0)} = 0.69 \frac{H}{H_{c2}(0)} \quad \mathcal{E}_m \equiv \mathcal{E}_m(t, h, z) = \ln \frac{1+z}{t} + \psi \left[\frac{1+z}{2} + \frac{2h}{t} \frac{(2m+1)}{\pi^2} \right] - \psi \left(\frac{1}{2} \right)$$

A. Glatz, A. A. Varlamov, and V. M. Vinokur, EPL 94, 47005 (2011)
A. Glatz, A. A. Varlamov, and V. M. Vinokur, PRB 84, 104510 (2011)

$$\gamma_\phi = \frac{\pi \hbar}{8k_B T_c \tau_\phi}$$

Cooper Channel

$$t = T/T_c \quad \gamma_\phi = \frac{\pi\hbar}{8k_B T_c \tau_\phi} \quad \rightarrow \quad \tau_\phi^{-1} = \frac{\pi k_B T}{\hbar} \cdot \frac{e^2 R}{2\pi^2 \hbar} \ln \frac{\pi\hbar}{e^2 R}$$



Superconducting fluctuations

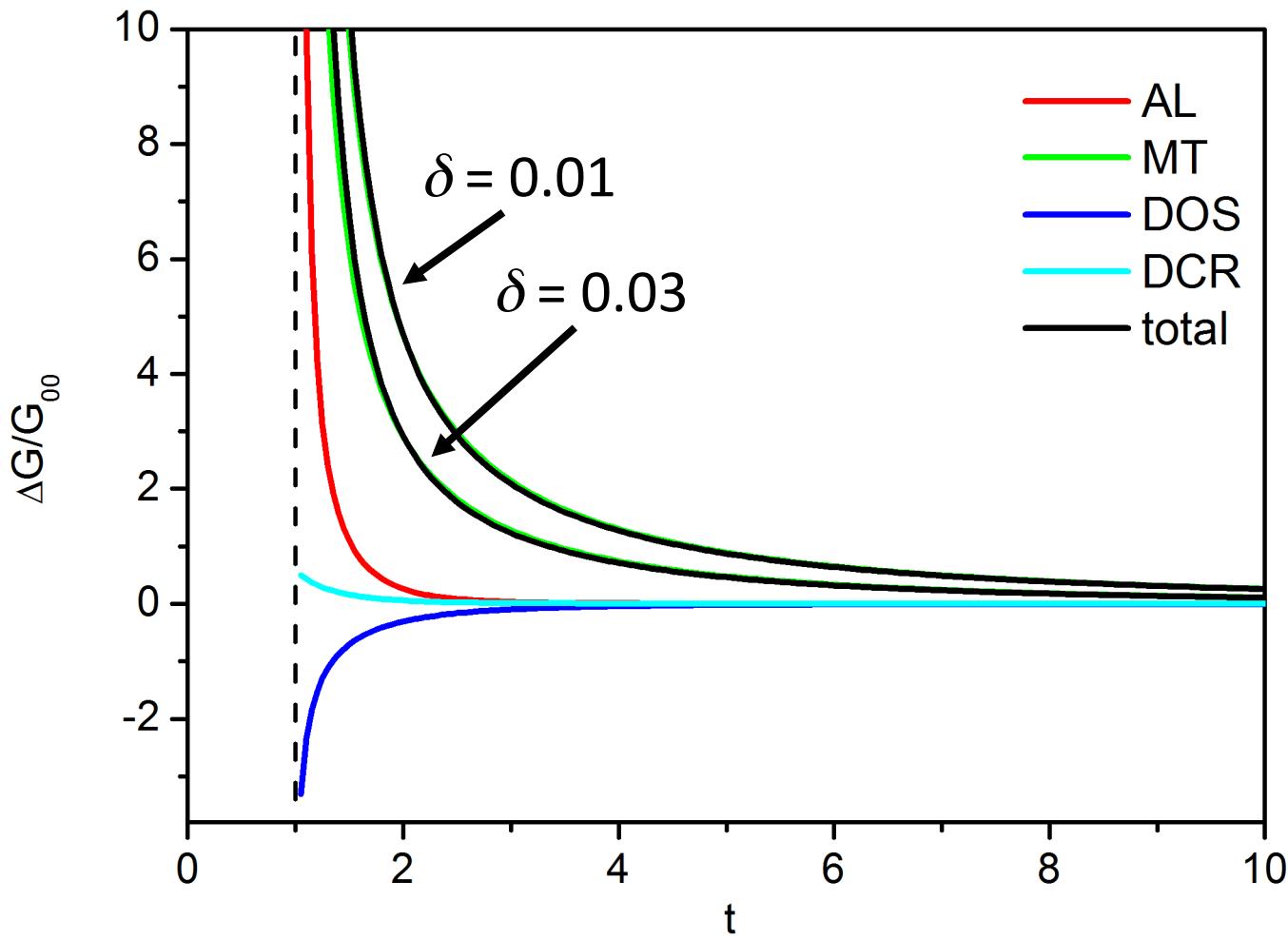
$$\begin{aligned} \tau_\phi^{-1} &\propto T \\ \delta &= \frac{\pi\hbar}{8k_B T \tau_\phi} \\ \gamma_\phi &= \delta \cdot t \end{aligned}$$

Cooper Channel

$$t = T/T_c \quad \gamma_\phi = \frac{\pi\hbar}{8k_B T_c \tau_\phi} \quad \rightarrow$$

Superconducting fluctuations

$$\tau_\phi^{-1} = \frac{\pi k_B T}{\hbar} \cdot \frac{e^2 R}{2\pi^2 \hbar} \ln \frac{\pi\hbar}{e^2 R}$$

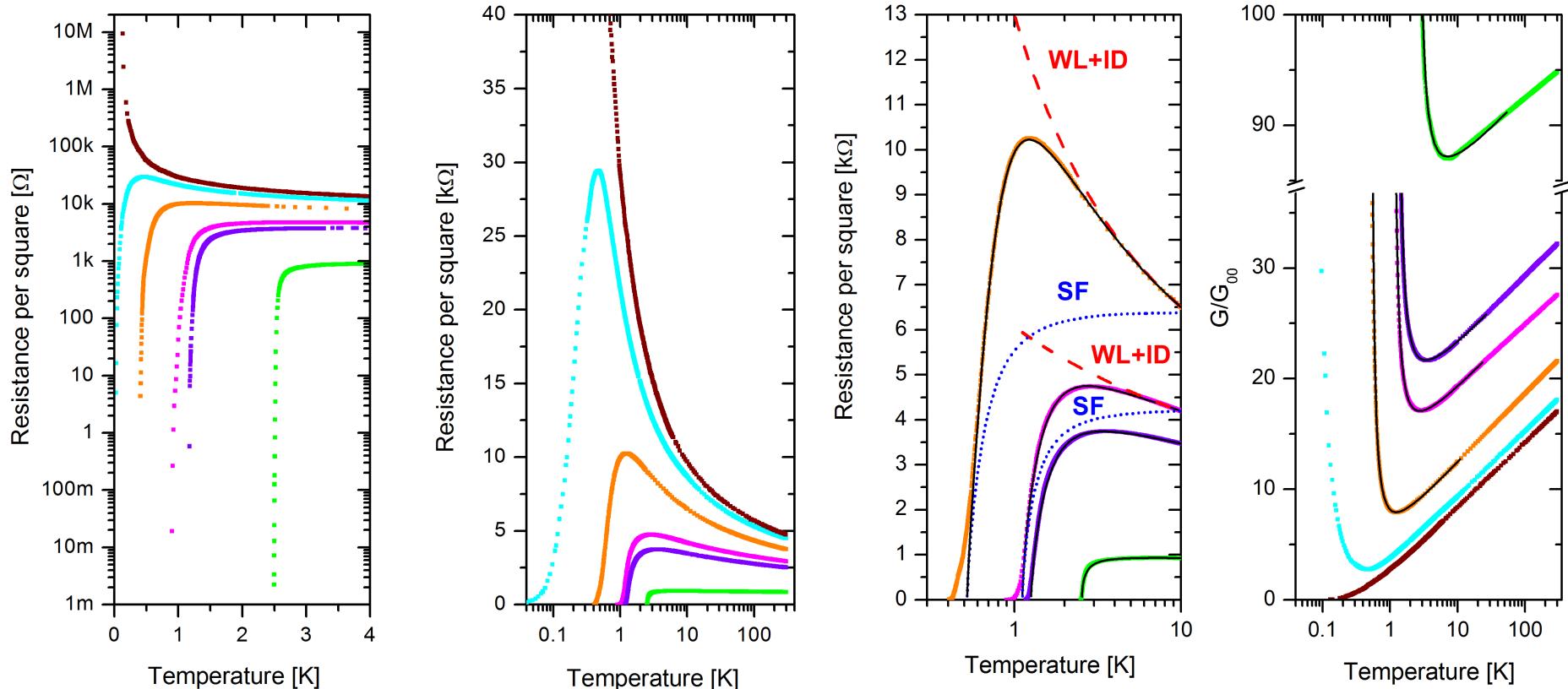


$$\begin{aligned} \tau_\phi^{-1} &\propto T \\ \delta &= \frac{\pi\hbar}{8k_B T \tau_\phi} \\ \gamma_\phi &= \delta \cdot t \end{aligned}$$

$$\delta = \frac{e^2 R}{16\hbar} \ln \frac{\pi\hbar}{e^2 R}$$

Evolution of Superconductivity with Increasing Disorder in Two Dimensions

Non-monotonic behavior of $R(T)$!!



Drude conductivity
+

quantum contributions: weak localization, e-e interaction, superconducting fluctuations

$$R^{-1} = G_0 + \Delta G^{WL+ID} + \Delta G^{SF}$$

the resistance of thin films on the superconducting side of the transition exhibits **non-monotonic** temperature behavior due to the competition between the weak localization, electron-electron interaction, and superconducting fluctuations.

This rules out the existence of the horizontal separatrix between superconducting and insulating states and indicates the meaningless of scaling procedure much too often used for the description of the SIT.

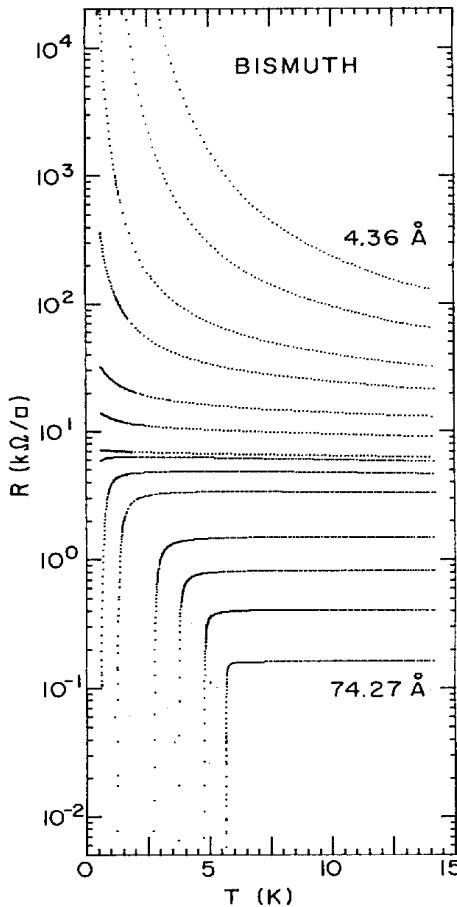
Other materials

Evolution of Superconductivity with Increasing Disorder in Two Dimensions

negative dR/dT

Is it conclusive for the choice of the state?

$$R_c = h/(2e)^2$$



Does the universal resistance for SIT exist?

Fan-shaped curves

D.V. Haviland, Y. Liu, and A.M. Goldman, PRL 62, 2180 (1989)

$d < d_c$ Insulator

d_c Metal

$d > d_c$ Superconductor

Bi films
 $R_c = 6.45 \text{ k}\Omega$

The onset of superconductivity in homogeneous ultrathin films is found to occur when their normal-state sheet resistance falls below a value close to $h/4e^2$, the quantum resistance for pairs. The data fur-

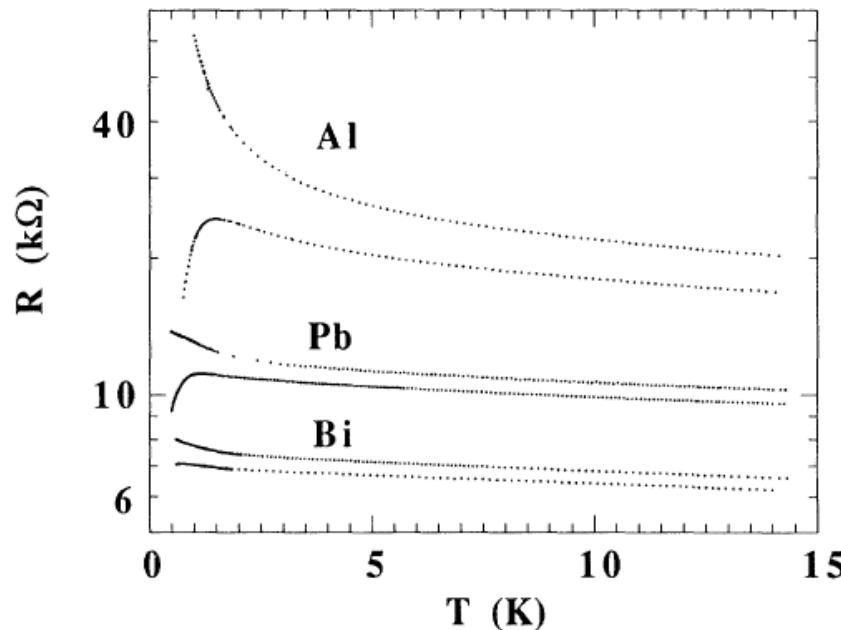
Evolution of Superconductivity with Increasing Disorder in Two Dimensions

negative dR/dT

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$$R_c = h/(2e)^2$$

Does the universal resistance for SIT exist?



Y. Liu, D.V. Haviland, B. Nease, and A.M. Goldman, PRB **47**, 5931 (1993)

FIG. 7. Sheet resistance R vs T of the first superconducting and last insulating films for the Bi, Pb, and Al sequences. The algebraic mean R_0 of the resistance at 14 K of the last insulating and first superconducting films of the Bi, Pb, and Al sequences, respectively, are 6.42, 9.94, and 18.6 kΩ. These numbers are close to $h/4e^2$, $1.5(h/4e^2)$, and $3(h/4e^2)$, and appear to be system dependent.

Pb, Al films
 $R_c \neq 6.45 \text{ k}\Omega$

Evolution of Superconductivity with Increasing Disorder in Two Dimensions

negative dR/dT

Is it conclusive for the choice of the state?

$$R_c = h/(2e)^2$$

Does the universal resistance for SIT exist?

SIT

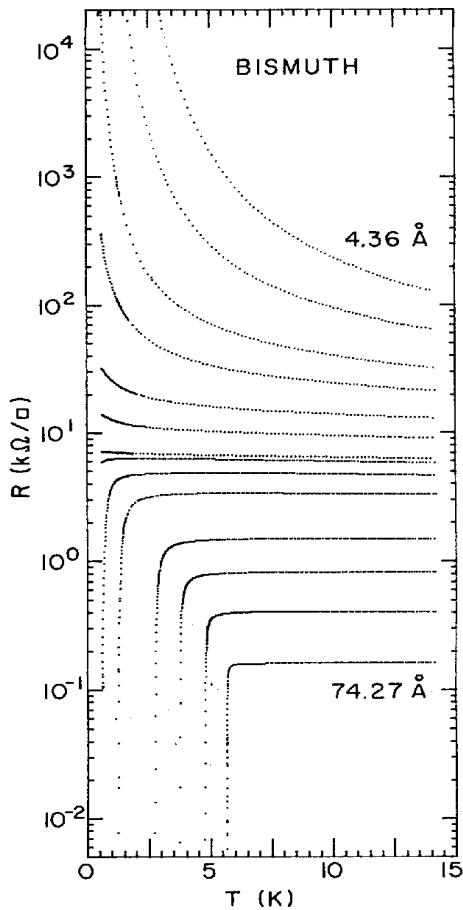
✓ the resistance at the transition was found
to deviate significantly
from the expected universal value

$$R_c = h/(2e)^2$$

At present there is no any theoretical prediction establishing the upper limit for disorder which preventing superconducting ground state

Evolution of Superconductivity with Increasing Disorder in Two Dimensions

D.V. Haviland, Y. Liu,
and A.M. Goldman,
PRL **62**, 2180 (1989)



Y. Liu, D.V. Haviland, B. Nease, and
A.M. Goldman, PRB **47**, 5931 (1993)

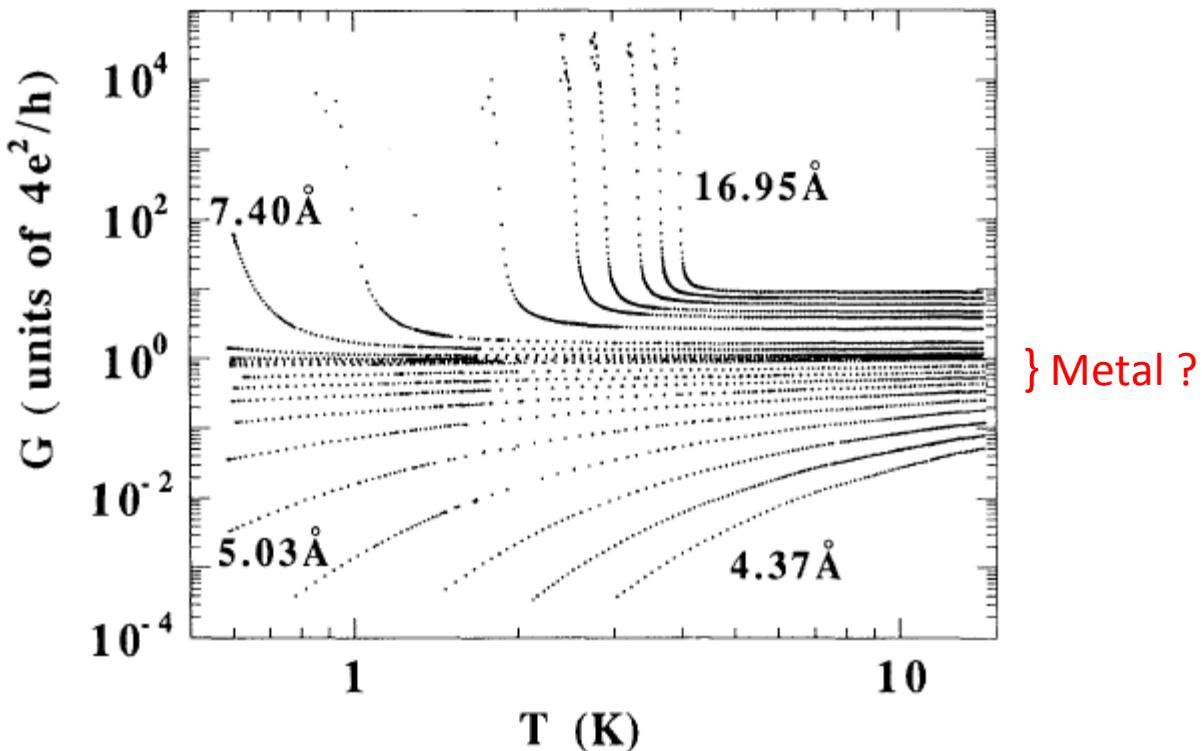
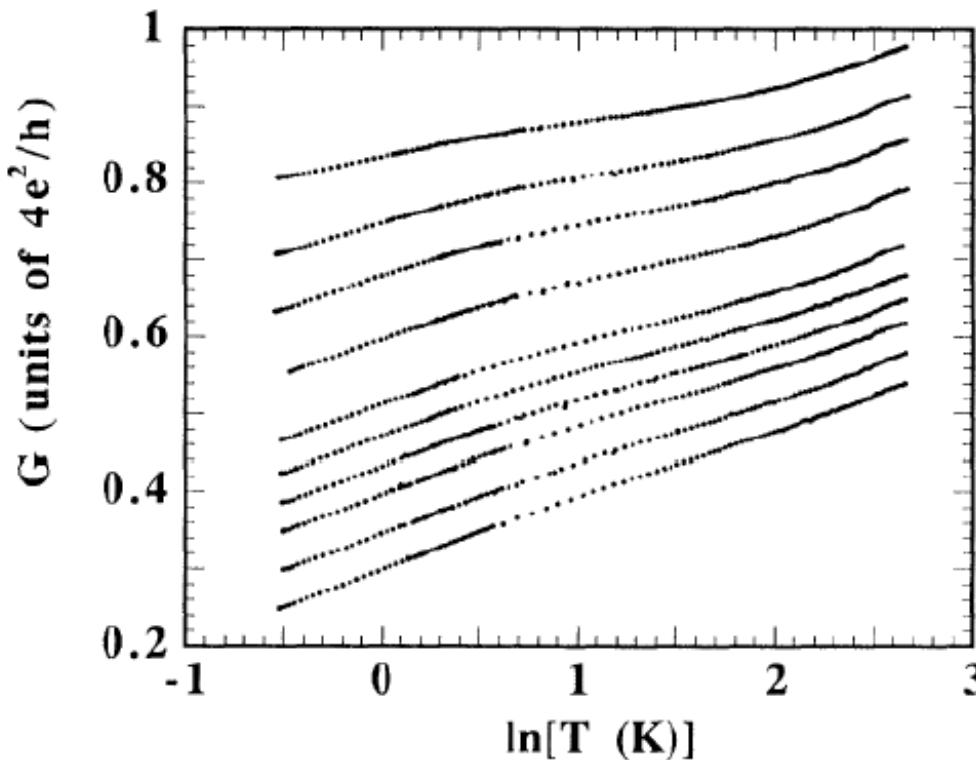


FIG. 2. Evolution for Bi films of the electrical conductance G in units of $4e^2/h$ as a function of temperature T . The thicknesses of a few selected films are indicated. Note that conductance and conductivity are identical in two dimensions. Only some of the data of the sequence of films is shown to avoid too high a density of data points.

Evolution of Superconductivity with Increasing Disorder in Two Dimensions

Bi films



Y. Liu, D.V. Haviland, B. Nease, and
A.M. Goldman, PRB **47**, 5931 (1993)

$$G \propto \ln T$$

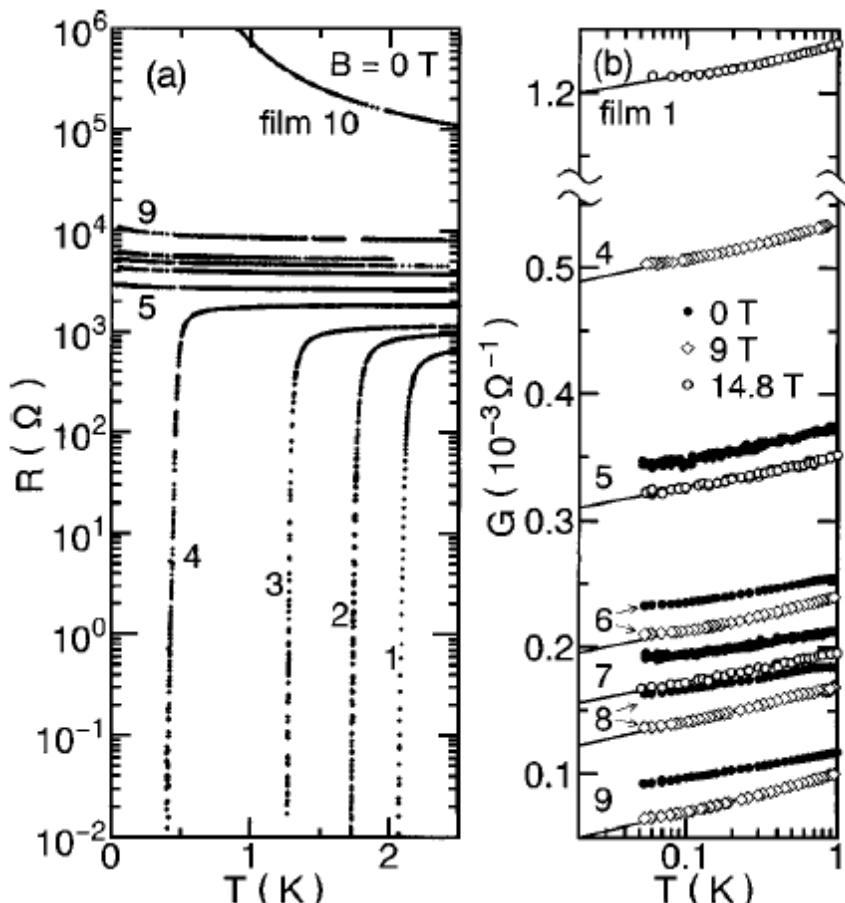
} M?

metal
Drude conductivity
+
quantum contributions

FIG. 6. Conductance G vs $\ln T$ of last ten insulating Bi films. (The 22nd to 31st films of the Bi sequence.) The temperature dependences of the conductances are approximately logarithmic. Notice that in the low-temperature limit, the slope of the logarithm decreases as the onset of superconductivity is approached.

SMIT

Evolution of Superconductivity with Increasing Disorder in Two Dimensions



Mo_xSi_{1-x} films

S. Okuma, T. Terashima, and Kokubo,
PRB 58, 2816 (1998).

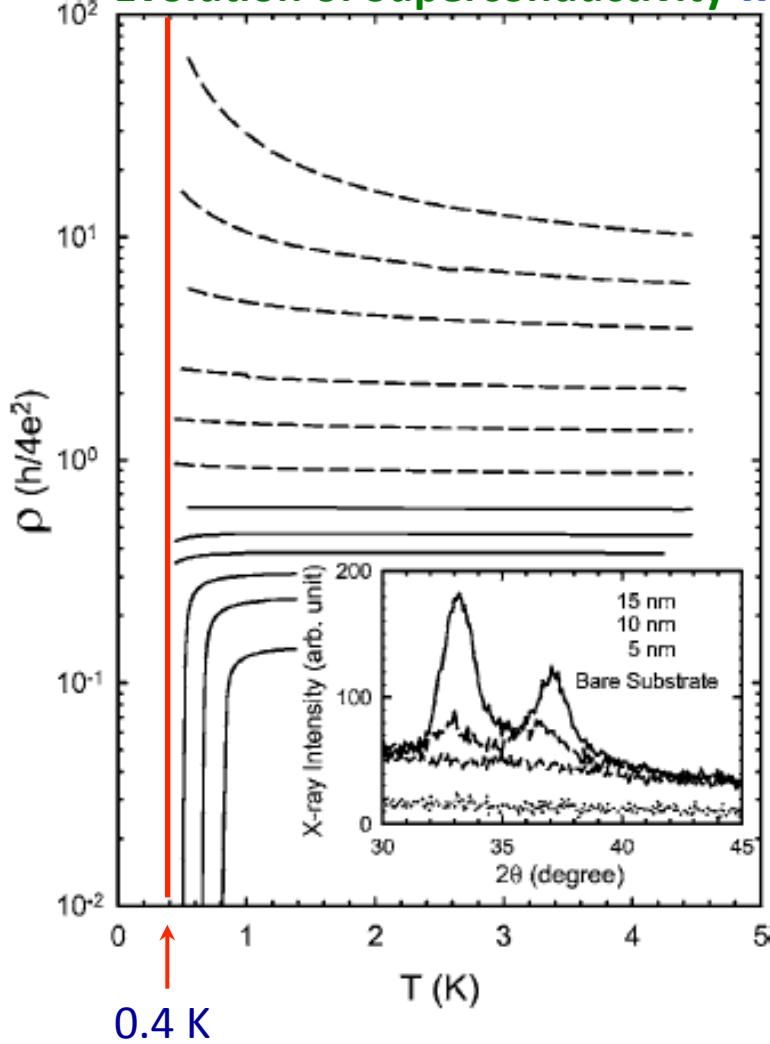
$$G \propto \ln T$$

metal
Drude conductivity
+
quantum contributions

Figure 1(a) illustrates the temperature dependence of the sheet resistance $R(T)$ in $B=0$ for ten selected films. Films with $R_n(10 \text{ K})$ smaller than $1.8 \text{ k}\Omega$ (films 1–4) achieve global superconductivity, while those with $R_n(10 \text{ K})$ larger than $2.5 \text{ k}\Omega$ (films 5–10) behave like an insulator, showing an increase in R at low temperatures.

SMIT

Evolution of Superconductivity with Increasing Disorder in Two Dimensions



Ta films

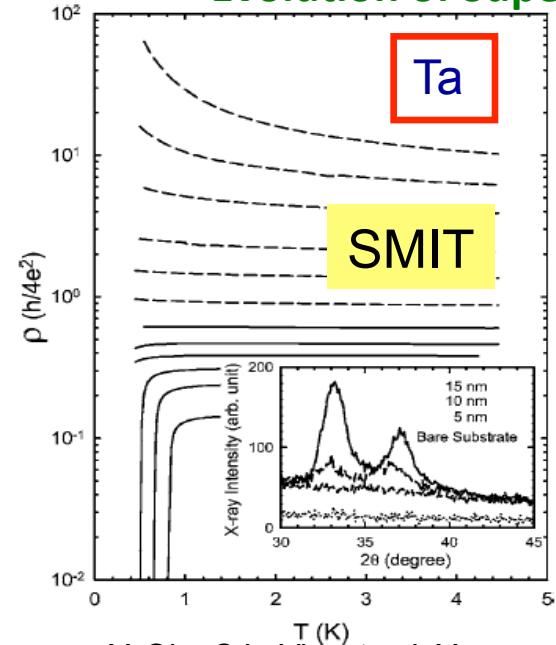
Y. Qin, C.L. Vicente, J. Yoon,
PRB 73, 100505(R) (2006).

← 6.45 kΩ

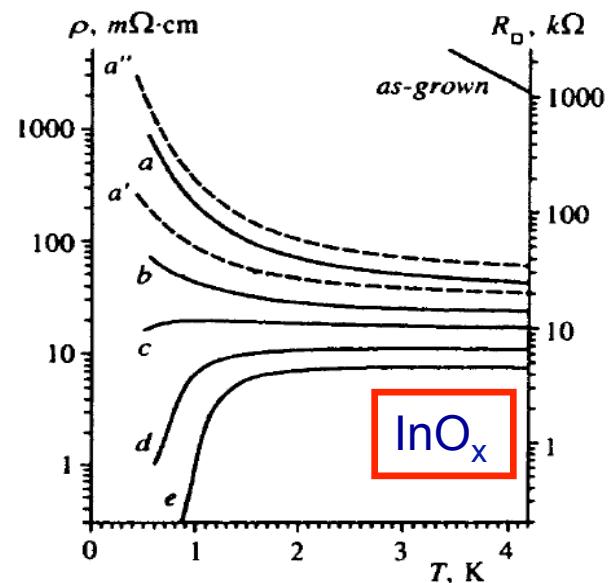
SMIT

FIG. 1. The resistance is measured at $B=0$ with a dc current in the range 1–10 nA that is within the linear response regime. The thicknesses of the films are, from the top, 1.9, 2.0, 2.1, 2.3, 2.5, 2.8, 3.1, 3.4, 3.7, 4.0, 4.5, and 5.5 nm. The dashed lines are for the insulating phase and the solid lines are for the superconducting phase. Inset: x-ray diffraction patterns of 15, 10, 5 nm thick Ta films, and a bare Si substrate.

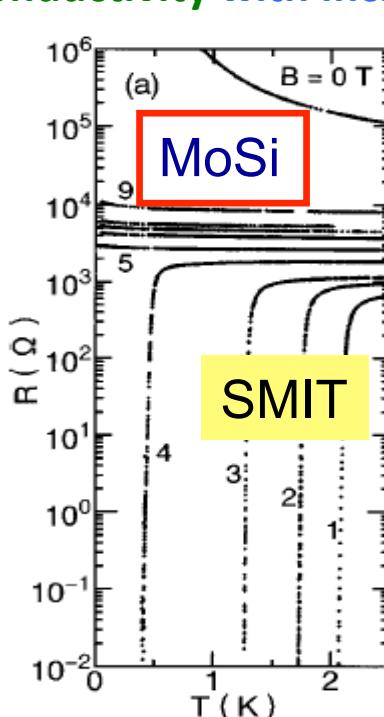
Evolution of Superconductivity with Increasing Disorder in Two Dimensions



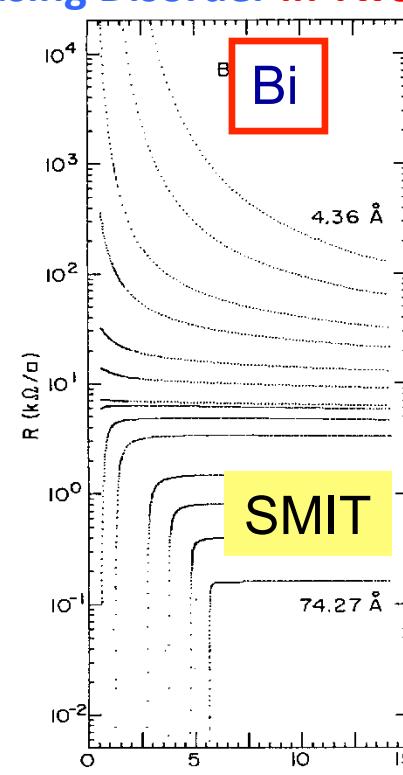
Y. Qin, C.L. Vicente, J. Yoon,
PRB 73, 100505(R) (2006).



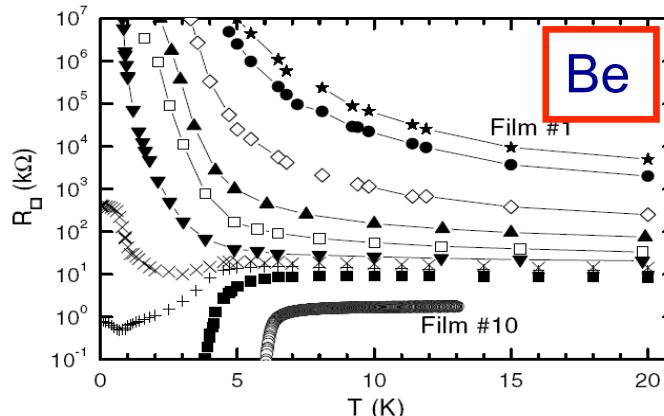
V.F. Gantmakher, M.V. Golubkov, J.G.S. Lok,
and A.K. Geim, JETP 82, 951 (1996).



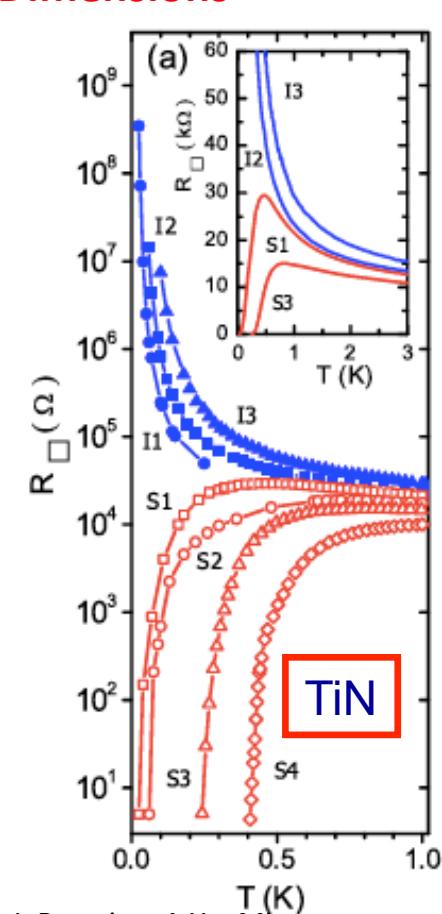
S. Okuma, T. Terashima,
and N. Kokubo,
PRB 58, 2816 (1998).



D.B. Haviland, Y. Liu,
and A.M. Goldman (1989)



E. Bielejec, J. Ruan, and W. Wu
PRL 87, 36801 (2001).

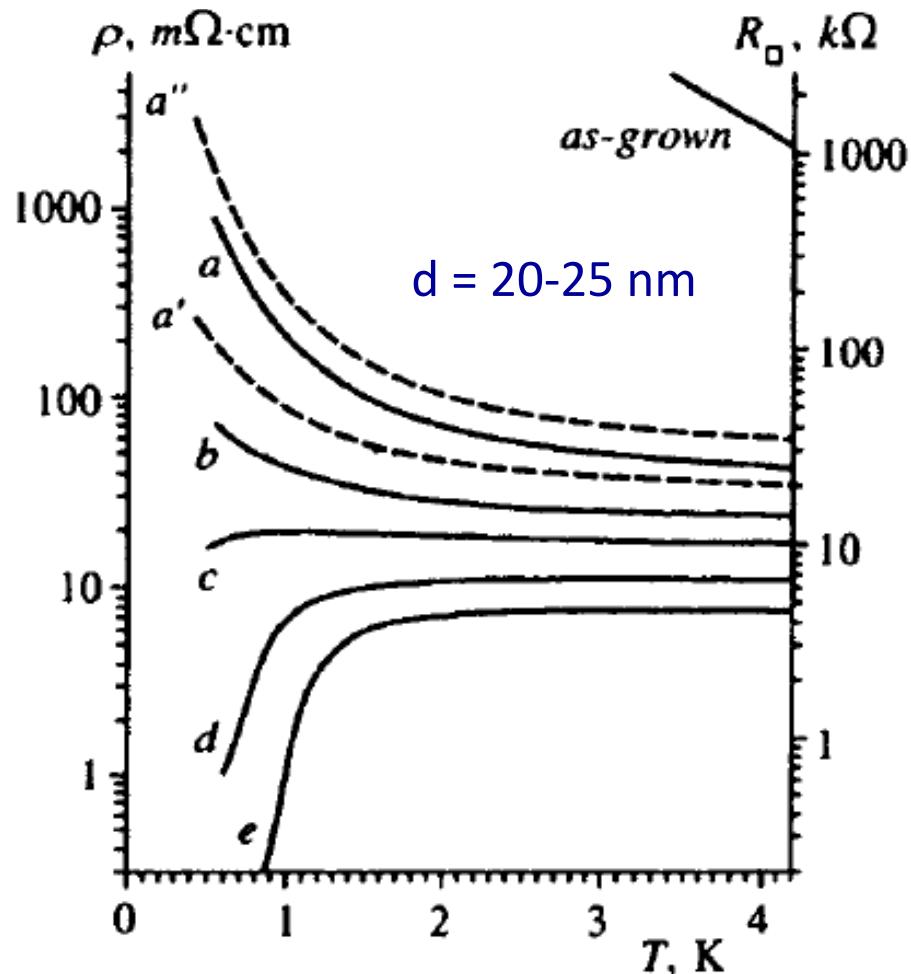


T. I. Baturina, A.Yu. Mironov,
V. M. Vinokur, M. R. Baklanov,
C. Strunk, PRL 99, 257003 (2007).

SIT or SMIT



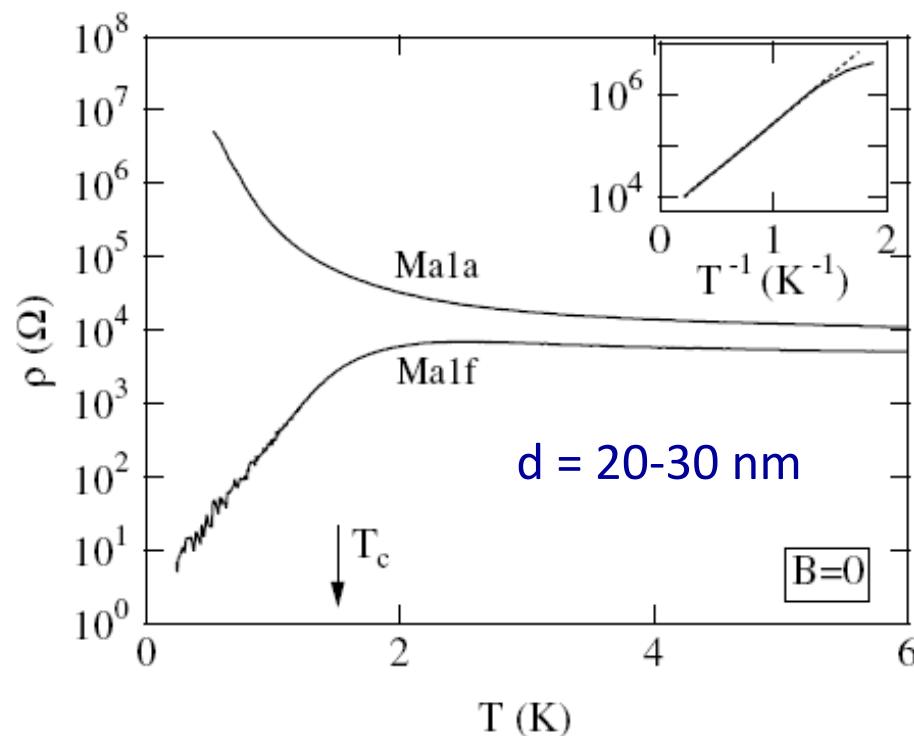
InO_x films



V.F. Gantmakher *et al.*,
JETP 82, 951 (1996).

FIG. 2. Evolution of the temperature dependence of the resistance of $a\text{-In}_2\text{O}_x$ films in zero magnetic field after different treatments. Film No. 1: states a (initial)– e , film No. 2: states a' (initial) and a'' . A part of the dependence $R(T)$ for the as-grown film from the inset of Fig. 1 is also plotted.

InO_x films



G. Sambandamurthy,
L.W. Engel,
A. Johansson,
and D. Shahar,
PRL 92, 107005 (2004).

FIG. 1. Zero magnetic field ρ versus T curves of a single film at two different stages of annealing, Ma1a and Ma1f. Ma1a is insulating with $T_I = 4.3$ K. Inset: ρ versus T^{-1} curve for Ma1a (solid line), and the fit to Eq. (1) (dashed line). At low T , deviation from the activated behavior is observed. Vertical arrow in the main figure marks T_c ($= 1.5$ K) of the superconducting film Ma1f.

Be films

E. Bielejec, J. Ruan, and W. Wu
PRL 87, 36801 (2001).

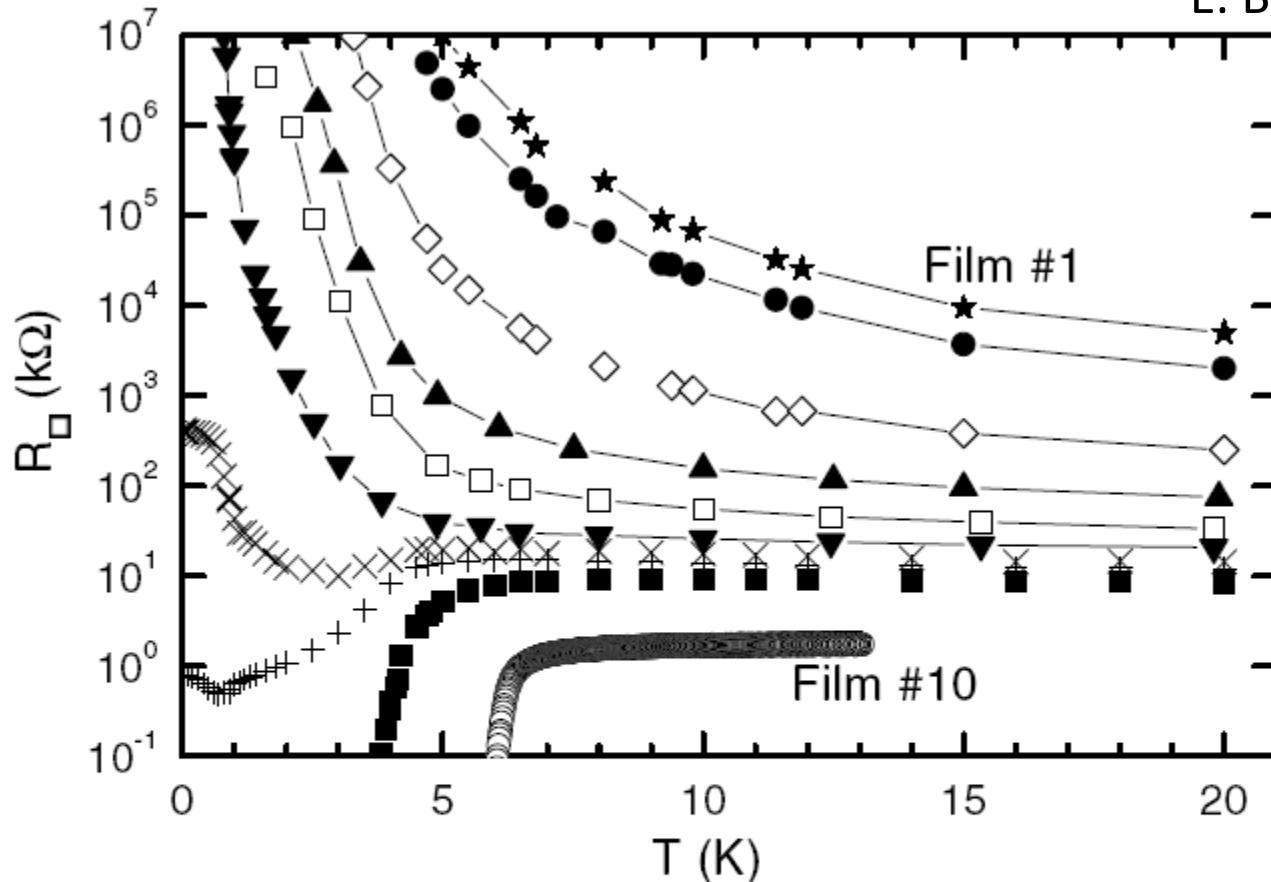


FIG. 1. Curves of film sheet resistance as a function of temperature measured on one film section following a series of deposition steps to increase film thickness. For curves from top to bottom, we label them as Film #1 to Film #10, respectively. The thickness for these films changed from 4.6 to 15.5 Å.

Be films

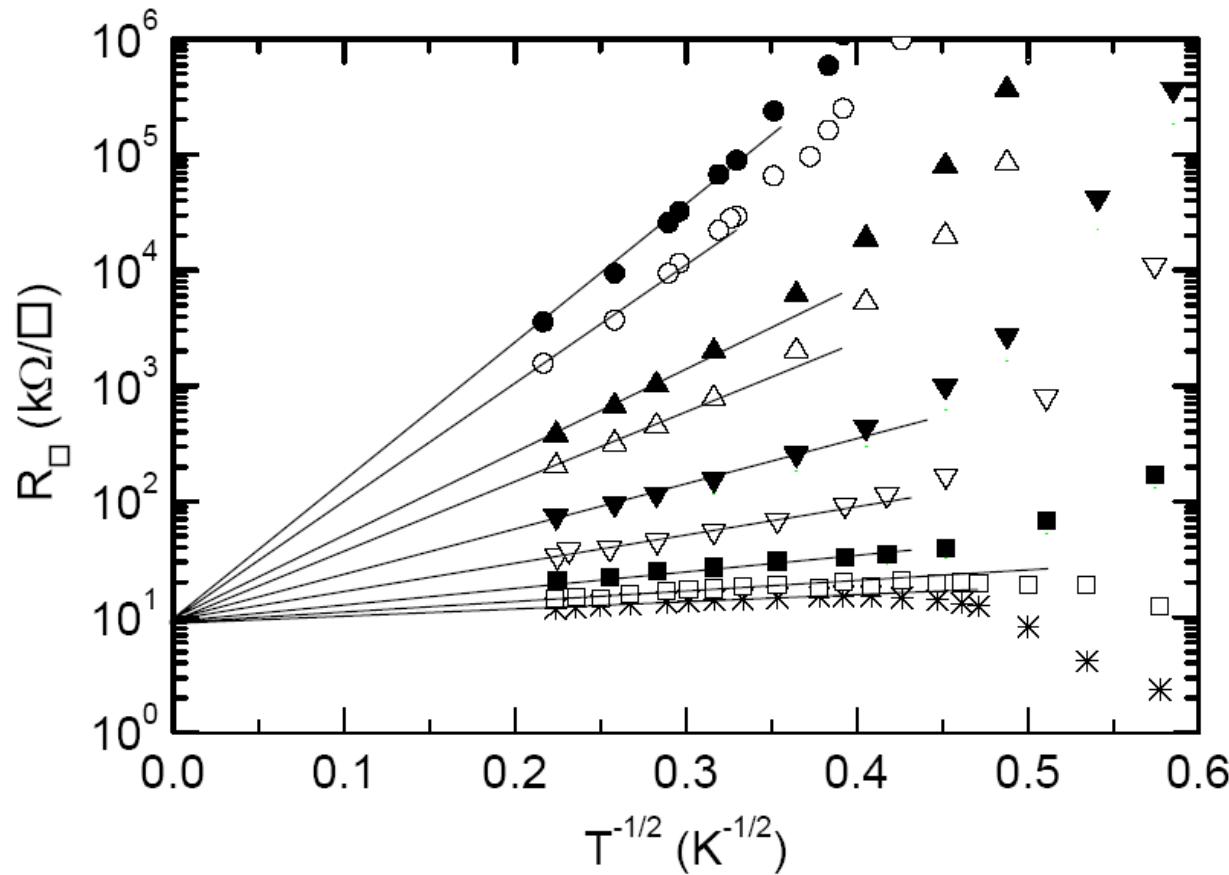
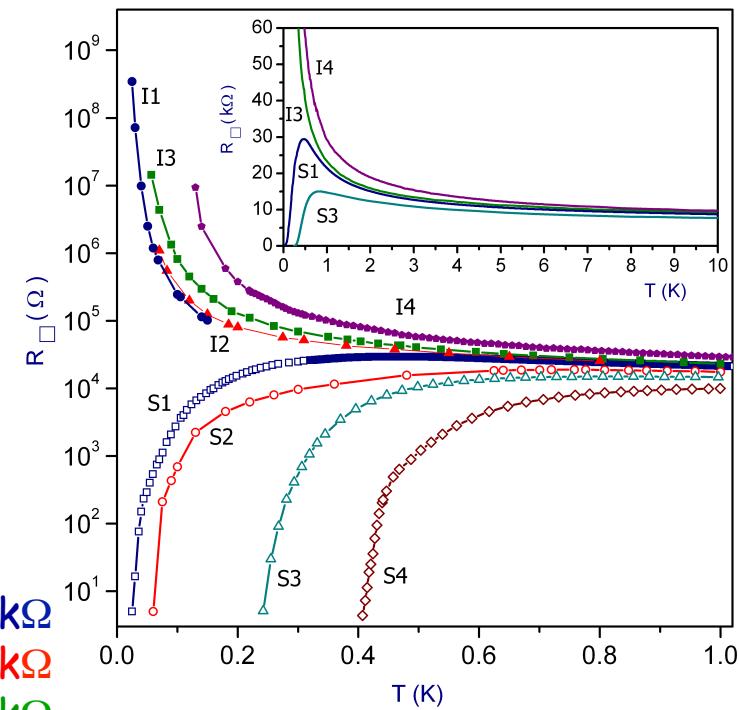
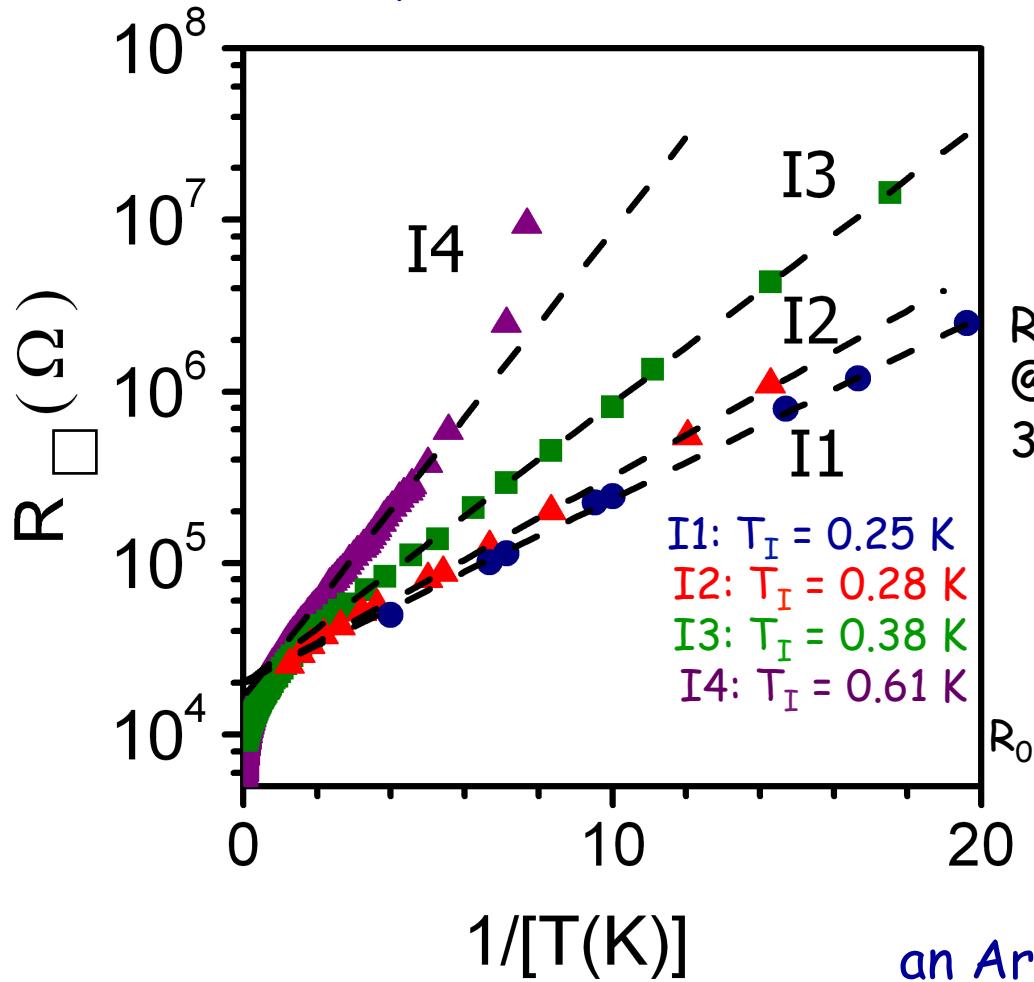


Fig. 1 Selected curves of R_{\square} versus $1/T^{1/2}$ for one Be film section following deposition steps to increase film thickness (from top to bottom). The thickness for these films changed from 4.6 \AA to about 10 \AA . The straight lines are drawn as a guide for eye, showing that in the high-T regime all the curves follow straight lines that converge to about $10 \text{ k}\Omega/\square$ in the $T \rightarrow \infty$ limit. The films for bottom curve is superconducting at low temperatures.

At lower temperatures...



$$R = R_0 \exp(T_I/T)$$

an Arrhenius behavior of the resistance

- T. Baturina, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk, PRL 99, 257003 (2007)
 T. Baturina, A. Bilušić, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk, Physica C 468, 316 (2008)
 T. Baturina, A.Yu. Mironov, V. Vinokur, M.R. Baklanov, C. Strunk, JETP Lett. 88, 752 (2008)

Evolution of Superconductivity with Increasing Disorder in Two Dimensions

The search for a disorder-driven superconductor-insulator transition has included many materials, e.g.,

Bi, MoSi, Ta, InO_x, Be, TiN.

The immediate onset of exponential temperature dependence of the resistance, which conclusively evidences
the direct transition into an insulator,

was found so far only in **InO_x, Be, and TiN** films.

For **Bi, MoSi, and Ta**-compounds a weak logarithmic temperature dependence of the resistance was observed on the nonsuperconducting side in the vicinity of the transition.